Study on Porous Pavement for Water Management Including Use of Piezoelectricity

Thesis

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Debashish Karmakar

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Dedicated

to my

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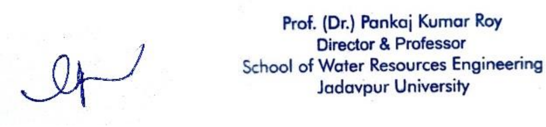
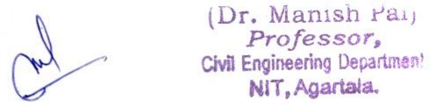


Prof. Pankaj Kumar Roy
Professor and Director
School of Water Resources Engineering
Jadavpur University
Kolkata, INDIA



Prof. Manish Pal
Professor
Civil Engineering Department
NIT Agartala
Agartala-799046, INDIA

Dr. Kaberi Majumdar
Associate Professor
Electrical Engineering Department
Tripura Institute of Technology,
Agartala -799009, INDIA

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Name of the Candidate: **Mr. Debashish Karmakar**

Signature of the Candidate:

Date: 29/11/2023

Location: Kolkata

Certified by Supervisor(s):
(Signature with date & seal)

Prof. (Dr.) Pankaj Kumar Roy
Director & Professor
School of Water Resources Engineering
Jadavpur University

Prof. Pankaj Kumar Roy
Professor and Director
School of Water Resources Engineering
Jadavpur University
Kolkata-32, INDIA

Prof. Manish Pal
Professor
Civil Engineering Department
NIT Agartala
Tripura-799046, INDIA

(Dr. Manish Pal)
Professor,
Civil Engineering Department
NIT, Agartala.

Dr. Kaberi Majumdar
Associate Professor
Electrical Engineering Department
Tripura Institute of Technology
Agartala -799009, INDIA

(DR. KABERI MAJUMDAR)
Associate Professor
Deptt of Electrical Engineering
TIT, Narsingarh
Government of Tripura

CERTIFICATE FROM THE SUPERVISORS

This is to certify that the thesis entitled **"Study on Porous Pavement for Water Management Including Use of Piezoelectricity"** submitted by **Mr. Debashish Karmakar,** Index No: D-7/ISLM/83/18, who got his name registered on **03.01.2019** in the academic session **2019-2024** for the award of **Doctor of Philosophy in Engineering** from **Jadavpur University,** is absolutely based upon his own work under the supervision of **Prof. Pankaj Kr. Roy, Prof. Manish Pal & Dr. Kaberi Majumdar,** and that neither his thesis nor any part of his thesis has been submitted for any degree / diploma or any other academic award anywhere before.

Certified by Supervisor(s):
(Signature with date & seal)

Prof. (Dr.) Pankaj Kumar Roy
Director & Professor
School of Water Resources Engineering
Jadavpur University

Prof. Pankaj Kumar Roy
Professor and Director
School of Water Resources Engineering
Jadavpur University
Kolkata-32, INDIA

Prof. Manish Pal
Professor
Civil Engineering Department
NIT Agartala
Tripura-799046, INDIA

(Dr. Manish Pal)
Professor,
Civil Engineering Department
NIT, Agartala.

Dr. Kaberi Majumdar
Associate Professor
Electrical Engineering Department
Tripura Institute of Technology
Agartala -799009, INDIA

(DR. KABERI MAJUMDAR)
Associate Professor
Deptt of Electrical Engineering
TIT, Narsingarh
Government of Tripura

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LIST OF ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CMOS	Complementary Metal-Oxide-Semiconductor
CNSA	Coarse Natural Stone Aggregate
CPX	Close-Proximity
CR	Crumb Rubber
CSSA	Coarse steel slag aggregates
dB	Decibel
dBA	A-weighted decibel
DBS	Dibenzylidene sorbitol
DC	Direct Current
FEA	Finite Element Analysis
GGBS	Ground-granulated blast furnace slag
GPS	Global Positioning System
HMA	Hot Mix Asphalt
HoV	High-occupancy vehicle
HVB	High-viscosity binder
HVS	Heavy Vehicle Simulator
IDT	Indirect Tensile Strength
ISI	Indian Standards Institute
LDPE	Low-density polyethylene
LED	Light-emitting diode
MoRTH	Ministry of Road Transport & Highways
NAPA	National Asphalt Pavement Association
NSA	Natural stone aggregates
OBC	Optimum Binder Content
OBSI	On-Board Sound Intensity
OGAC	Open Graded Asphalt Concrete
OGFC	Open Graded Friction Course
OPC	Ordinary Portland Cement
PA	Porous asphalt
PAC	Porous Asphalt Concrete
PC	Pervious concrete
PCA	Plastic Coated Aggregate
PG	Piezoelectric generator
PICP	Permeable Interlocking Concrete Pavement
PZT	Lead Zirconate Titanate
RCPT	Rapid Chloride Permeability Test
RMSE	Root Mean Square Error
RPA	Rubberised Polymer Asphalt
SF	Silica Fume
SPB	Statistical Pass-By
SSA	Steel Slag Aggregate
TPS	Taf Pack Super
UNHSC	University of New Hampshire Storm water Center
VA	Air Voids
VFB	Voids filled with bitumen

VMA	Voids in mineral aggregate
w/c	Water-cement
WWII	World War II

ABSTRACT

This dissertation comprehensively explores improvements and applications of porous pavement innovations in various engineering contexts. The primary focus is on enhancing the performance of porous pavements, particularly Porous Asphalt (PA), by incorporating crumb rubber into the Open-Graded Friction Course (OGFC) bituminous mix. The study aims to increase strength and stability without compromising permeability, which is essential for successful water percolation. Furthermore, the research seeks to identify suitable crumb rubber combinations for bituminous mixes on medium to moderate traffic volume roads.

The investigation begins with an examination of Permeable Asphalt Pavement, which offers significant advantages in reducing water runoff, enhancing water quality, and increasing skid resistance during heavy rainfall. The goal is to strengthen Porous Asphalt while maintaining its permeability for groundwater replenishment. Laboratory experiments assess the features of Rubberized Porous Asphalt (RPA) compared to traditional OGFC bituminous mixtures. The findings indicate that RPA with 1% crumb rubber content and 5% Optimum Bitumen Content (OBC) demonstrates significantly higher stability than conventional PA mixtures under mild traffic loads.

Additionally, the study explores the optimization of Porous Concrete, a sustainable environmental technology, for low-volume road applications. Through adjustments in cement-water ratio, aggregate gradation, and fine aggregate content, various test samples are generated to evaluate flexural durability, permeability, tensile and compressive strength, and porosity. The structural and hydrological properties of porous concrete are improved when Ground Granulated Blast Furnace Slag (GGBS) is used as a partial cement substitute, providing a workable option for constructing permeable concrete layers on low-volume highways.

Furthermore, the research investigates the use of LDPE-coated aggregates in permeable bituminous pavements to enhance performance under moderate traffic loads. This study explores an unconventional and successful approach for environmentally friendly plastic disposal and addresses pavement moisture vulnerability with an anti-stripping compound. The findings reveal that a 0.50% LDPE concentration in the open graded porous bituminous mix yields acceptable Marshall Stability values and outperforms the standard mix.

The investigation extends to the structural behavior of porous asphalt mixes with partial substitution of stone particles with steel slag. The study examines the impacts of steel slag, a sustainable substitute for natural stone aggregates, on mechanical properties and structural characteristics of porous asphalt mixes. Laboratory mix design procedures with varied amounts of steel slag are conducted, along with tests involving Marshall Stability, permeability, and Cantabro abrasion. Steel slag replacement improves the mechanical and structural qualities of the combinations, particularly at 20% and 40% replacement rates, respectively. Additionally, the study focuses on the effect of steel slag concentration on porosity and permeability, demonstrating that while porosity declines with increasing steel slag concentration, it remains within acceptable boundaries for porous asphalt mixes.

The thesis also investigates the effect of coarse aggregate dimensions and forms on the permeability and compressive strength of permeable concrete. The results indicate that the form and size of aggregates significantly impact permeability and compressive strength, suggesting that employing irregular-shaped aggregate with a specified water-cement ratio achieves the desired balance.

Lastly, the study explores harvesting energy from pedestrian movement over piezoelectric material, with or without rubber strips, to meet rising energy demands sustainably. Data analysis shows that piezoelectric materials embedded with rubber strips outperform those without, and the Series Parallel Combination (SPC) of piezoelectric materials proves superior to Parallel Series Combination (PSC). The generated energy can be stored in supercapacitors to address modest energy needs, such as illuminating roadside LED lights or charging cell phones.

Porous pavement innovations are crucial in engineering and sustainability, providing environmentally conscious solutions to urban challenges like storm-water runoff, water quality, and energy consumption. These innovations hold great promise in creating more sustainable and resilient urban environments while fostering efficient water management, reduced noise pollution, and renewable energy harvesting.

Keywords: *Open-Graded Friction Course (OGFC) bitumen mix, Porous Asphalt (PA), Rubberized Porous Asphalt (RPA), Optimum Bitumen Content (OBC), Marshall Mix design, Water cement ratio, Aggregate binder ratio, Porous Bituminous Pavement, Low Dense Polyethylene (LDPE), Moisture Susceptibility, Anti-Stripping Agent, Plastic Coated Aggregates (PCA), Marshall Mix Design, Porous Concrete (PC), Compressive strength, Tensile strength, Flexural strength, Permeability, Ground Granulated Blast Furnace Slag (GGBS), Steel slag aggregate, Cantabro test, Flakiness index, Angularity number,*

Piezoelectricity, Energy harvesting, Super capacitors, Noise pollution, Pedestrians energy, Piezo embedded footpath, Ground Water Recharge, Marshall Stability, Flow, Marshall Quotient, Traffic Volume.

CHAPTER-1

INTRODUCTION

1.1 GENERAL

Due to increasing population and the spread of civilization as a whole, there is a growing demand for sustainable and eco-friendly solutions to the issues posed by these trends. The destruction of forests and expanding development in rural regions are the key repercussions of rapid urbanisation and industrialisation. This has made a negative impact on the ecosystem, notably the increase in deforestation and its consequences.

Despite the benefits of porous asphalt, past research has revealed several mechanical and performance limits. To address these constraints, researchers have concentrated on improving the properties of Open Graded Friction Course (OGFC) the bituminous mixture by introducing crumb rubber. The major goal is to increase the durability and efficiency of porous pavements, particularly on medium-traffic highways. Rubberized asphalt binder, which combines asphalt with crumb rubber from used tyres, has showed promise in improving pavement surface longevity and rutting resistance.

Water table depletion is another key environmental issue covered in the paper, which is a serious concern in many Indian towns. By enabling rainfall to travel through each layer and permeate into the soil subgrade, permeable bituminous pavement is presented as a viable method for replenishing groundwater. Pervious concrete is an ecologically friendly pavement material with an open-graded structure that is appropriate for pathways, sidewalks, parking lots, and low-volume roadways. However, due to necessity of bearing traffic loads while retaining water percolation, its implementation in carriageway construction offers issues.

To increase the durability and strength of pervious concrete, several additions such as polyethylene fibres, crumb rubber, steel slag and GGBS have been examined.

One research focuses on the significance of acceptable binding in pervious concrete in order to endure traffic stresses and allow for water percolation. Ground-granulated blast furnace slag (GGBS) is being studied as a cementitious material with good bonding capabilities in the mix. According to the findings, Concrete's bending and compressive qualities can be enhanced by GGBS while still allowing for water percolation.

Another research looks at the usage of permeable asphalt to provide a wearing layer in the construction of roads to further investigate the viability and advantages of porous pavements. The research looks at how porous asphalt manages precipitation, reduces traffic noise, and improves road surface conditions. Porous asphalt helps with the management of water, filtration, and recharge of groundwater by enabling water to enter through the asphalt layer. It also has the ability to minimise noise pollution caused by motor traffic.

Another research focuses on energy harvesting through piezoelectric transduction technology. As the need for power is growing and worries about the environmental implications of existing energy sources are growing, experts are looking into alternate means of producing electricity that are not harmful to the environment. Piezoelectric power generation has emerged as a potential technology for capturing energy from piezoelectric crystal deformation. In this research, piezo crystals are implanted in pathways, and the movement caused by walkers creates electricity, resulting in a sustainable and environment friendly energy-generating solution.

In brief, this chapter presents an overview of the significant environmental concerns caused by urbanisation, highlighting the possible benefits of porous pavements and novel technologies such as piezoelectric transduction energy harvesting. The study intends to provide useful insights into the application of these technologies in the construction of roads, with potential advantages for the management of water, noise mitigation, and energy generation. The parts that follow will go into further depth on porous pavements, permeable asphalt mixes using slag from steel as an alternative for stone aggregate, and gathering energy from walkways. These studies aim to solve particular concerns, enhance pavement performance, and give long-term solutions for future road building projects.

1.2 Overview of porous pavement:

Pervious pavement, additionally referred to as permeable pavement, appears to be standard pavement at first appearance, but it has deliberate gaps that allow it to be porous. This indicates that the pavement has holes in its construction that enable water to travel through and penetrate the ground beneath. Ferguson established the notion of pervious pavement in 2005, categorizing it into two main types: monolithic pavement and modular pavement.

A monolithic pavement is a solid, bonded construction made up of permeable concrete and porous asphalt. The pavement itself is porous in this design, allowing water to soak through its surface and into the earth. In this category, porous concrete as well as porous asphalt are often employed because they provide efficient permeability while maintaining the structural integrity necessary for normal traffic loads.

Modular pavement, on the other hand, is made out of a network of linked pieces, or pavers, each with porous properties. Porous aggregate, porous grass, polymeric geo-cells, open-jointed paving blocks, concrete grid pavers, soft paving components, and deck systems are all examples of these units. The modular approach provides design and installation flexibility as well as simplicity of maintenance.

Porous aggregate pavers are made up of linked aggregate pieces that allow water to infiltrate. Porous turf pavers have a surface made of grass or vegetation, which promotes rainwater drainage as well as green spaces in urban areas. Plastic geo-cells are structures with three dimensions that serve as a sturdy foundation for permeable fill materials and enable water to flow through. Open-jointed paving blocks are interconnecting components with holes between them that allow water to pass through. Concrete grid pavers provide a long-lasting surface with open gaps for water to flow through. Rubber pavers and other soft paving materials have flexibility and permeability. Finally, deck systems are made out of raised platforms that enable water to flow beneath them.

In general, pervious pavement systems help with storm water management by minimizing runoff and encouraging groundwater recharge. They are used in a variety of situations, including as parking lots, pathways, driveways, and even roadways, and contribute to sustainable urban development.

1.2.1 Background of porous pavement:

Pervious concrete (PC) was first proposed by Europeans in 1852 for the construction of residential walls. Due to lack of traditional building materials after WWII, various nations in Europe and the United States started to utilise pervious concrete as a pavement option. Pervious concrete pavement has risen in popularity in the United States over the last several decades, with Florida being the very first state to deploy full-blown pervious concrete pavement, owing to its hydrological features.

Pervious concrete has seen a renaissance in the building sector globally in recent years, owing to the necessity to fulfil ecological and meteorological regulatory requirements. Pervious concrete pavements have been adopted by several nations as an eco-friendly option and an attractive alternative to regular pavements. Pervious concrete's distinctive open-pore structure allows rainfall to either seep into a subsurface storage basin or immediately exfiltration into the earth, so helping to promote groundwater recharge. Furthermore, the material possesses the ability to remove contaminants from water, resulting in an environment benign solution for urban pavements.

The fundamental goal of pervious concrete is to accumulate, treat, and enable unrestricted penetration or transfer of surface runoff. Therefore, it increases groundwater recharge and plays an important part in storm water management. Pervious concrete, by allowing water penetration, can replace ineffective and wasteful sewage systems, facilitating the shift to sustainable drainage systems rather than conventional "end-of-pipe" drainage methods.

Aside from handling storm water, pervious concrete pavement has various other advantages. It can help to lower noise levels in cities by absorbing sound energy and acting as a barrier against noise. Furthermore, photo catalyst agents can be included within the pavement matrix to improve the material's capability to absorb pollutants such as NOx and organic volatile compounds, hence enhancing urban air quality.

Pervious concrete also improves road safety by increasing tire-pavement friction, lowering the chance of cars skidding, especially under wet weather conditions. Additionally, it reduces reflections of light and night glare, increasing driver sight.

Pervious concrete's numerous benefits have led to its broad acceptance in a variety of nations, and its eco-friendliness qualifies it for Excellence in Energy and Environmental Design, also known as EEED, awards. Pervious concrete has been designated as a Best Management Practise (BMP) for storm water management by the Environmental Protection Agency (EPA).

However, despite its various advantages, pervious concrete has significant restrictions that prevent its broad application. Because of its low strength and structural capability, the material is best suited for parking lots, low-volume roadways, walkways and residential streets. Permeable concrete may not have the structural capability required for high-volume roadways and intensively used motorways. Further, one of the biggest difficulties with permeable concrete pavement is its proclivity to clog with time, potentially lowering hydraulic conductivity and rate of infiltration. Nonetheless, continuing research intends to remove these limitations and increase the structural capabilities of the material.

1.2.2 Advantages of porous pavement:

Porous pavement, also known as permeable pavement, consists of a surface that enables water to pass through and enter the ground underneath it. It has following benefits over standard impermeable surfaces such as concrete or asphalt.

1. **Rainwater management:** One of the key benefits of porous pavement includes its capacity to properly control rainwater. It decreases surface runoff by enabling rainfall to penetrate the pavement and absorb the soil beneath. This helps to replenish groundwater, to reduce the load on rainwater drainage systems, reduce the danger of erosion and flooding.

2. **Water quality enhancement:** As rainfall runs over porous pavement, it filters naturally, removing pollutants and toxins. The method aids in the improvement of the water's quality in local bodies of water such as streams, rivers, and lakes, lessening the detrimental effects of urban runoff on the aquatic ecosystems.

3. **Reduced heat island effect:** Porous pavement absorbs less heat than standard impermeable surfaces such as concrete or asphalt. This reduces the urban heat island effect, in which cities become much hotter than their rural surrounds, urban heat island effect results in higher consumption of energy and heat-related health hazards.

4. **Improved groundwater recharge:** Porous pavement enhances groundwater recharge by enabling precipitation to sink into the earth. This contributes to the preservation of healthy levels of groundwater, which are essential for sustaining plants, supporting ecological systems, and offering a safe supply of drinking water.

5. **Improved site drainage:** Conventional pavements can leave puddles and stagnant water on the ground, which can be dangerous and unsightly. Water does not pool on the surface of porous pavement, making it more secure for pedestrians and automobiles. It also minimises the need for expensive drainage infrastructure.

6. **Extended pavement lifespan:** Contrary to popular belief, permeable pavement can have an extended lifespan than standard pavements. Water accumulating as well as freeze-thaw cycles can minimise deterioration, leading to fewer potholes and cracks as time passes.

7. **Cost reductions:** Although the initial expenses for the installation of porous pavement are slightly greater than those of regular pavements, but long-term expense reductions can be significant. Reduced maintenance, the possibility of simpler storm water drainage systems, and longer pavement lifespan all improve overall cost-effectiveness.

8. **Environmental benefits:** Porous pavement enhances environmental sustainability by retaining natural water cycles and reducing the need for substantial storm water management infrastructure. It is ecologically benign and compatible with green building as well as sustainable programmes, resulting in an environmentally aware alternative for both urban and housing developments.

9. **Aesthetically pleasing:** Perforated pavement may be made to seem nice. It provides design versatility by permitting the incorporation of various materials and patterns. This versatility improves the general appearance of the paved area and opens up new creative possibilities for architects and urban planners.

10. **Regulatory compliance:** Local rules in many areas promote or even demand the use of permeable pavement to solve storm water drainage and environmental problems. Choosing permeable pavement can assist builders and property owners in meeting these objectives while adhering to environmental rules.

Porous pavement, in summary, provides numerous benefits, like efficient storm water drainage, improved quality of water, decreased heat island effect, recharge of groundwater, extended pavement lifespan, reduced expenses, and positive effects on the environment. It makes porous pavement an environmental friendly and innovative solution for current urban development.

1.2.3 Disadvantages of porous pavement:

Porous pavement has several drawbacks that also should be considered when considering before utilising it.

1. **Reduced load-bearing capacity:** When compared to regular impermeable pavements, porous pavement usually has lower compressive strength. This loss in load-bearing capability may limit its application in high-traffic locations or where extensive structural support is required, such as industrial regions or busy motorways.

2. **Clogging and decreased permeability:** Sediment, debris, and organic material can clog the pores in the pavement over time. This blockage reduces the pavement's infiltration of water and drainage capacity, resulting in less effective stormwater management.

3. **Requirements for routine maintenance:** Regular maintenance, cleaning, and elimination of debris are required to prevent blockage and maintain the permeability of the surface.

4. **Frost heave and freeze-thaw damage:** When temperatures drop below freezing, water within the pores of the pavement can freeze and expand, generating frost heave and potential surface damage. The cycles of freeze-thaw can cause fractures and shorten the life of the pavement.

5. **Limited applicability in cold climates:** Perforated pavement may not be the greatest choice for areas with hard winters, since water penetration and freezing can exacerbate damage and shorten the pavement's lifespan.

6. **Contamination risk:** Pollutants like oily substances, toxic substances, and chemicals can build inside the pores of the pavement due to its porous nature. These contaminants can eventually be discharged into the surroundings or pollute groundwater supplies, creating environmental problems.

7. **High Initial cost:** The initial cost of permeable pavement is often greater than the cost of standard impermeable pavement. The cost of specialised materials and building processes may raise the original project costs.

8. **Limited design possibilities:** When compared to traditional pavements, porous pavement may have less possibilities for design in terms of colours, patterns, and textures, which may limit its usage in particular architectural or aesthetic purposes.

9. **Weed growth:** The porous pavement's open pores can create an ideal habitat for weed growth. Weeds can grow through the surface, necessitating additional upkeep measures to control them and keep the pavement looking nice.

10. **Complexity of installation:** Porous pavement needs rigorous preparatory work and installation to assure appropriate performance. Improper installation can result in decreased permeation, structural instability, and greater maintenance requirements.

Despite these drawbacks, porous pavement remains an important alternative for storm water management, lowering urban heat island impacts, and supporting sustainable development. However, before choosing porous pavement, it is critical to analyse the unique site characteristics, planned usage, and maintenance capabilities to assure its long-term efficacy and cost-efficiency.

1.3 Sustainable development of porous pavement:

The use of eco-friendly practices and materials in the design, construction, and maintenance of porous pavements is referred to as the environmental conscious development of porous pavement. Porous pavement is a porous surface that allows rainfall to percolate through it, minimising runoff and encouraging groundwater recharge. It has several environmental advantages, such as storm water management, decreased urban heat island impact, and enhanced water quality. Here are some critical considerations for the long-term advancement of porous pavement:

1. **Material selection:** For the porous pavement, use sustainable materials which include reclaimed aggregate, crushed concrete, or porous interlocking concrete pavers. Using locally produced products can help in decreasing the environmental effect of transportation.

2. **Considerations for design:** Ensure that the pavement design fulfils the unique needs of the location and its planned use. Proper design is required to maximise rainwater infiltration, to reduce clogging, and to assure the lifespan of the pavement.

3. **Maintenance:** Regular maintenance is required for the porous pavement. This involves cleaning the surface, removing dirt, and fixing any clogging difficulties. It is critical to use eco-friendly cleaning practices and chemicals to ensure the pavement's long-term viability.

4. **Water quality control:** Implement pre-treatment methods to guarantee that contaminants are filtered out of water before it enters the ground. Biofiltration, vegetated swales, and other filtration techniques may be applied.

5. **Porous base:** The foundation beneath the permeable pavement should be permeable as well, so that it can allow for adequate water penetration and to prevent precipitation or saturation.

6. **Education and outreach:** Inform people in general, municipal governments, as well as other stakeholders regarding the beneficial effects of permeable pavement including its role in promoting sustainable growth.

7. **Monitoring and evaluation:** Evaluate the efficacy of the porous pavement on a regular basis to ensure that it is performing as planned and meets its sustainable goals. Feedback and data accumulated over time can be used to make adjustments.

8. **Urban planning:** Porous pavement should be included into urban planning and development initiatives to maximise its benefits across a larger region. Porous pavements might be integrated into parking lots, walkways, and other urban surfaces.

9. **Climate considerations:** When constructing porous pavements, one must take into consideration the local temperature and precipitation patterns. Designing for extreme weather occurrences ensures that the system stays functional over time.

10. **Incentives and policies:** Use incentives, subsidies, or policies for sustainable development to encourage the use of porous pavement. Governments and non-governmental organisations may play an important role in encouraging and promoting sustainable practises.

We may take substantial steps to achieve healthier and more eco-friendly urban settings by incorporating these ideas into the creation and management of porous pavement projects.

1.3.1 Importance of sustainable development of porous pavement:

Sustainable construction of permeable pavement is critical for a variety of reasons, including social, environmental, and economic advantages. Here are some of the most important aspects of the long-term evolution of porous pavement:

1. **Storm water management:** One of the key advantages of permeable pavement is its capacity to efficiently regulate storm water runoff. Porous pavement minimises the amount and intensity of runoff by enabling rainfall to soak into the ground, hence preventing floods and erosion in metropolitan areas.

2. **Groundwater Recharge:** Groundwater recharge is facilitated by porous pavement, which allows precipitation to soak through the surface layer and fill subsurface aquifers. This contributes to the preservation of optimal levels of water in wells and the long-term viability of local water supplies.

3. **Improved water quality:** When rainwater infiltrates via porous pavement, natural filtering processes occur, eliminating pollutants and toxins before they reach bodies of water. This contributes to better quality of water in the surroundings.

4. **Lower urban heat island effect:** Traditional impermeable pavements, such as asphalt and concrete, lead to the urban heat island effect, which causes greater temperatures in cities compared to rural areas. Porous pavement can help offset this impact and produce a cooler urban environment. It enables rainwater to cool its surface and boosting evapotranspiration.

5**. Increased green spaces:** The adoption of permeable pavement can allow for additional green spaces in urban settings, which adds aesthetic value, improves biodiversity, and boosts inhabitants' mental well-being.

6. **Climate change adaptation:** Sustainable porous pavement may be constructed to withstand extreme weather events such as excessive rainfall and flooding. Its ability to control rainwater can assist cities in adapting to varying climate conditions.

7. **Cost reductions:** While the initial expense of the installation of porous pavement may be greater than that for traditional pavement, long-term expense reductions can be substantial. Reduced maintenance costs and storm water management advantages the original expenditure over time.

8. **Sustainable urban development:** Porous pavement promotes more environmental friendly urban development by incorporating it into urban design. It is consistent with sustainable

development and green infrastructure concepts, rendering societies more resilient and ecologically responsible.

9. **Compliance with rules:** There are rules or incentives in some places that promote the installation of permeable surfaces in construction projects. Environmental friendly porous pavement can assist developers in meeting these standards and avoiding fines.

10. **Environmental leadership:** The use of sustainable porous pavement demonstrates an attachment to environmental conservation and sustainable practices. It can serve as a model for others and encourage more community-based sustainable efforts.

As a whole, the long-term sustainability of porous pavement is critical to the creation of resilient, ecologically conscious, and livable urban landscapes. Perforated pavement helps ensure an environmental friendly future for our cities and the earth as a whole by managing rainwater, increasing water quality, and decreasing the urban heat island effect.

1.3.2 Methods of sustainable development of porous pavement:

Implementing practices that improve performance while minimising environmental effect is essential for the long-term advancement of porous concrete both in terms of strength and quality. Here are some strategies for achieving long-term growth of the quality and strength of porous concrete:

1. **Material selection:** For porous concrete, use sustainable and locally produced resources that include reclaimed aggregate, fly ash, or slag. Using extra cementitious materials minimises the requirement for typical cement manufacturing, which consumes a lot of energy and emits a lot of CO_2.

2. **Optimal mix design:** Create the concrete mix with care to get the desired porosity as well as toughness. To get the optimal combination of strength and permeability, use proper amount of aggregates, cement, along with water.

3. **Permeability Enhancement:** Use chemicals or chemical admixtures to increase the ability to permeate of the concrete without sacrificing its strength. These chemicals can aid in the formation of a more interlinked pore structure, which allows water to move through more effectively.

4. **Curing:** Sufficient curing is required to guarantee that the strength of the concrete develops. Use eco-friendly curing technologies, such as reclaimed water or energy from renewable sources to manage the temperature throughout the curing process.

5. **Carbonation-Curing:** Carbonation curing is a procedure in which carbon dioxide is put into the concrete mix, enabling it to absorb CO2 from the surrounding atmosphere and spontaneously carbonate. This not only improves strength but also aids in carbon sequestration, resulting in a more sustainable solution.

6. **Aggregate gradation optimisation:** Selection and optimising the aggregate gradation carefully increases the durability as well as strength of the porous concrete. A properly graded aggregate mixture can help to eliminate voids and increase packing density.

7. **Fibre reinforcement:** Add recycled fibres or natural fibres such as hemp or bamboo to the mix of concrete to increase strength and decrease cracking.

8. **Quality monitoring and testing:** During manufacturing, use stringent quality control processes to verify the uniformity as well as the quality of the permeable concrete. Regular inspection of concrete samples identifies problems and enables for changes to the mix design as needed.

9. **Life cycle analysis:** Conduct a life cycle assessment, or LCA, to examine the environmental implications of porous concrete across its full life cycle, from raw material recovery through recycling at the end of life or disposal. Make educated judgements using the LCA data to pinpoint areas for improvement.

10. **Use of recycled water:** To minimise water use and save freshwater resources, consider utilising recycled water in the concrete mixing process.

11. **Recycled content:** To reduce the environmental effect of the material's extraction and manufacturing, use concrete containing a larger proportion of recycled materials, either in aggregates or cement.

Porous concrete may be constructed to fulfil essential strength and quality standards while supporting eco-friendly construction practises and lowering its carbon footprint by using these sustainable development strategies.

1.4 Sustainable development of porous pavement using alternative materials:

A praiseworthy way to promote eco-friendly and ecologically sensitive infrastructure is the creation of porous pavement employing salvaged and recyclable materials, both inorganic and organic in nature. Porous pavements are intended to enable water to percolate through their outermost layer and into the soil underneath, therefore reducing storm water runoff and alleviating drainage concerns. Incorporating salvaged and waste materials into their construction can improve their sustainability and help to reduce waste.

Here are some ways for creating long-lasting porous pavements:

1. **Recycled Concrete Aggregate (RCA):** Crushed concrete leftover from collapsed structures can be utilised as a base material or integrated into the permeable pavement mix as recycled concrete aggregate (RCA). This decreases the need for fresh aggregate mining while also encouraging recycling.

2. **Recycled plastic:** Plastic trash may be treated and used in permeable pavement mixes, increasing the flexibility and durability of the pavement while minimising plastic pollution.

3. **Scrap tyre rubber:** Shredded or ground rubber from used tyres may be added into the porous pavement mix to improve elasticity and increase fracture resistance.

4. **Fly Ash:** Fly ash, the by-product of power plants powered by coal, can be used as a cementitious mix of permeable pavements, eliminating the demand for regular cement and its environmental effect.

5. **Glass Cullet:** Recycled glass may be broken into tiny fragments (cullet) and included into the pavement mixture, improving surface texture and decreasing the usage of virgin resources.

6. **Organic Materials:** Including organic materials in the pavement mix, such as compost or biochar, can improve the state of the soil, help in stormwater filtering, and promote growth of vegetation alongside the permeable pavement.

7. **Permeable Interlocking Concrete Pavers (PICP):** PICP are concrete or clay pavers with spaces between them that enable water to permeate. They can use recycled materials and offer an attractive alternative to typical porous pavements.

8. **Green pavement systems:** By incorporating plant and grass into pavement design, frequently referred to as "green pavement," a more environmental friendly and visually pleasing surface may be created.

9. **Geotextiles:** Permeable fabrics can be utilised beneath permeable pavement to differentiate between layers of soil. It may provide stability, and improve water penetration.

It is critical to understand that the development and implementation of sustainable porous pavements necessitates careful assessment of local variables, climate, and traffic loads. Laboratory evaluations and field experiments are required to assure the pavement's performance and lifespan.

Furthermore, periodic upkeep and monitoring are required to keep porous pavements functional and in good shape for long-term sustainability.

1.4.1 Using crumb rubber:

The pursuit of sustainable urban development has been gaining substantial traction in recent years, driven by the compelling need to address environmental issues which include runoff from storm water, urban heat island effects, and the handling of waste. The use of crumb rubber being a replacement component in the development of permeable pavements has shown considerable promise among the novel alternatives that have evolved. Crumb rubber, which is made from recycled tyres, provides a unique chance to address two major concerns at the same time: decreasing environmental waste and building robust, eco-friendly infrastructures.

Traditional impermeable pavements intensify the negative effects of urbanisation by leading to rising runoff and decreased groundwater recharge, resulting in floods and water quality concerns. Porous pavements, on the other hand, allow rainfall infiltration, reducing storm water runoff and promoting natural groundwater replenishment. The problem, however, is to create permeable pavements that not just function well but also adhere to sustainable practices.

Crumb rubber, which is generated from old tyres via recycling procedures, is an appealing alternative for improving the efficiency and ecological aspects of permeable pavements. Its unique qualities, such as outstanding resilience, durability, and permeability to water, make it an ideal contender for increasing the mechanical behaviour and lifetime of pavements. Additionally, the use of crumb rubber helps address the growing problem of disposing of used tires by diverting them from landfills and lowering environmental concerns.

The purpose of this study is to investigate the feasibility and advantages of using crumb rubber as an alternate component for the creation of sustainable porous pavements. This study aims to shed light on the usefulness of crumb rubber in improving the integrity of the structure, hydraulic efficiency, and overall sustainability of porous pavements through extensive laboratory experiments and field assessments. This study's findings will add to the expanding body of information on sustainable development of infrastructure and pave the road for more environmentally conscious urban design practises. Finally, effective crumb rubber deployment in porous pavements might usher in a new age of sustainable and adaptable urban landscapes.

1.4.2 Using Ground Granulated Blast Furnace Slag (GGBS):

As cities face ever-increasing urbanisation difficulties, the construction of environmentally friendly infrastructure has become critical for minimising environmental consequences and maintaining resilient urban landscapes. The use of novel materials is critical in this effort, and one such potential option is Ground Granulated Blast Furnace Slag (GGBS). GGBS is a byproduct of the steel and iron processing sector that is produced during the iron manufacturing process in blast furnaces. Recognised for its outstanding environmental and technical properties, GGBS is establishing itself as a compelling choice for improving the long-term growth of porous pavements.

Conventional pavements greatly contribute to stormwater runoff, resulting in urban floods, deterioration of water quality, and decreased groundwater recharge. Porous pavements, on the other hand, provide an environmental benign alternative by enabling rainfall to enter the surface, minimising runoff, and recharging groundwater resources. However, creating permeable pavements that combine environmental advantages with their strength and lifespan is a problem.

Because of its advantageous qualities, GGBS is a suitable alternative material for the production of porous pavements. GGBS diverts garbage from landfills as a byproduct of industrial activities, reducing its environmental impact and supporting circular economy practises. Furthermore, when GGBS is added to a pavement mix, it improves mechanical attributes that include compressive strength as well as resilience, boosting the pavement's efficiency and lifetime.

The purpose of this study is to look at the feasibility and benefits of using GGBS as a substitute addition for the production of sustainable porous pavements. This study aims to investigate how GGBS effects the hydraulic behaviour, structural integrity, and general environmental sustainability of permeable pavements through extensive research in the laboratory and field assessments. The outcomes of this study will provide important insights into the optimisation of GGBS-based pavements and their significance in developing environmental aware urban infrastructure. Finally, the effective use of GGBS in permeable pavements may usher in a new age of ecologically benign, resilient, and environmental conscious urban construction.

1.4.3 Using Low Dense Polyethylene (LDPE):

The increasing urbanisation and related issues have sparked a global push towards the construction of sustainable infrastructure. The introduction of novel materials is critical in this endeavour, and one such potential option is the use of low-density polyethylene (LDPE). LDPE, a thermoplastic polymer, is gaining popularity due to its potential to revolutionise permeable pavement systems and promote ecologically aware urban landscapes.

Traditional impermeable pavements aggravate urban environmental challenges by creating significant stormwater runoff, which causes urban floods and reduces groundwater recharge. Porous pavements provide a long-term solution by enabling rainfall to percolate through the surface, minimising runoff and mitigating water-related issues. Optimising the efficiency of permeable pavements while maintaining long-term durability, on the other hand, is a big difficulty.

As an additive for the construction of sustainable porous pavements, LDPE provides a fresh and exciting possibility. LDPE inclusion in pavements, as a waste plastic product, diverts garbage from landfills, efficiently contributing to landfill waste reduction and encouraging circular economy concepts. Furthermore, the special qualities of LDPE, such as its flexibility, hydrophilic properties, and substantial tensile strength, show promise for improving the mechanical characteristics of the pavement, assuring endurance and durability.

The purpose of this study is to investigate the practicality and advantages of using LDPE as a substitute additive for the production of sustainable porous pavements. This study intends to investigate the influence of LDPE on the hydrodynamic behaviour, structural integrity, and overall environmental sustainability of permeable pavements through extensive laboratory experiments and field evaluations. This study's findings will provide critical insights into the optimisation of LDPE-enhanced pavements, opening the door for the incorporation of plastic waste into ecologically aware urban infrastructure.

This study aims to close the gap between reducing waste as well as sustainable urban development by utilising the prospective advantages of LDPE as a replacement material for porous pavements. Finally, successful use of LDPE in permeable pavements might be a game changer in developing adaptable, environmentally conscious and environmentally friendly societies of the future.

1.4.4 Using steel slag:

The incorporation of materials that are environmental friendly has become more important in the aim of sustainable urban development. Steel slag, a by-product of the steelmaking process, has emerged as an appealing alternative addition for improving the long-term development of permeable pavements. Porous pavements provide an innovative way to alleviate storm water runoff, minimise floods, and encourage groundwater recharge as cities cope with the issues faced by urbanisation. Obtaining the optimal balance between environmental advantages and pavement performance, on the other hand, remains a critical concern in this discipline.

Steel slag has the potential to revolutionise permeable pavement systems as well as contribute to more environmentally aware urban infrastructure. Steel slag, which is produced during the manufacturing of steel, diverts trash from landfills and minimises the environmental load related to its disposal. By introducing slag from steel production into the pavement mixture, the mechanical qualities of the permeable pavement, such as strength under compression and wear resistance, may be improved, resulting in greater lifetime and durability.

This research's objective is to look into the feasibility and benefits of employing slag from steel production as an alternative addition for the long-term advancement of porous pavement. This study tries to figure out how steel slag effects the hydraulic behaviour, strength, and general environmental sustainability of permeable pavements through extensive research in the laboratory and field evaluations. This study's findings will provide vital insights into the optimisation of steel slag-based roadways, opening the path for more robust and environmentally friendly urban environments.

This study seeks to close the gap between the minimising waste and ecological urban infrastructure by utilising the possible application of slag from steel production as a substitute substance for porous pavements. Finally, the effective use of slag from steel production in porous pavements might not only help facilitate more efficient waste management, but also to the construction of resilient and ecologically conscious cities. Accepting slag from steel production as an innovative ingredient is a huge step forward in the pursuit of sustainable urbanisation and the development of more sustainable more sustainable communities.

1.5 Effects of shape and size of coarse aggregate (CA):

Because of its capacity to enhance stormwater management, minimise surface runoff, and lessen urban heat island effects, permeable concrete has become popular as an environmental friendly and sustainable paving alternative. This novel material is made up of a cementitious structure as well as coarse aggregates, both of which are important in defining the functioning properties of the porous pavement. The form and size of coarse particles have a significant impact on the general porosity, permeability, mechanical properties, and durability of porous concrete.

Angular and flaky coarse aggregates are two types of coarse aggregates commonly utilised in porous pavement. Angular aggregates have sharp and uneven forms, whereas flaky aggregates have flat and elongated particles. Each aggregate type has distinct structural and hydraulic qualities that can have a major influence on the behaviour and efficiency of the porous pavement.

The purpose of this research is to look at the Impacts of Shape and Size of Coarse Aggregate upon Porous Concrete, with a particular emphasis on the various improvements in various qualities. We may learn more about how angular and flaky aggregates affect the porosity, permeability, flexural and compressive strength, and durability during freezing and thawing processes of porous pavement by systematically comparing them. Understanding these property enhancements is critical for optimising porous concrete design and performance in a variety of environmental and load-bearing circumstances.

A thorough experimental method will be used in the study, which will include mix design optimisation, testing in the laboratory, and performance assessment. The findings of this study will add to the expanding body of knowledge on sustainable pavement components and will be useful to engineers, urban planners, along with regulators looking for novel stormwater drainage as well as sustainable urban infrastructure solutions.

Finally, studying the effect of coarse aggregate shape and size on the characteristics of porous concrete can help us better understand the material's behaviour and performance. We can enhance the advancement of permeable pavements and help contribute towards more efficient and resilient urban settings by finding the best aggregates for specific applications.

1.6 Noise pollution on highway due to traffic:

Noise pollution on roads caused by car tyres moving is a major environmental hazard. This is usually referred to as "road traffic noise." The primary source of noise is the contact between the tyres and the road's surface as cars drive at high speeds. This sort of noise pollution is caused by a number of reasons, including:

1. **Surface material:** The noise intensity produced from various road surface materials varies. Concrete roads, for example, are louder than asphalt roads because to their coarser texture, which causes more friction with the tyres.

2. **Vehicle speed:** Driving at higher speeds amplifies the noise produced by tire-road contact. Both the frequency and magnitude of noise increase as cars go faster.

3. **Traffic volume:** The number of cars on the route has a direct impact on the total noise level. More automobiles means more noise from collective tyre movement.

4. **Tire design:** The shape and construction of the tyres can also affect the quantity of noise produced. Noise levels during mobility can be influenced by tread patterns and materials.

5. **Road maintenance:** Poor road maintenance, such as cracks, potholes, or surfaces that are uneven, can amplify noise levels owing to higher tyre vibrations and collisions.

1.6.1 Impact of noise pollution:

The effects of roadway noise pollution caused by tyre movement are diverse and can harm both the natural environment as well as human health:

A. **Impact on the environment:**

1. Wildlife environments and behaviour patterns are disrupted, potentially having a severe impact on local ecosystems.

2. Noise pollution can discourage species from crossing roadways, resulting in fragmentation of habitat and decreased biodiversity.

3. It can interfere with animals' natural interaction and navigation systems, such as those of birds and insects.

B**. Impact on the Health:**

1. Extended exposure to noise from traffic can cause anxiety, stress, and sleep difficulties in those who live close.

2. High levels of noise have been linked to cardiovascular difficulties and other health concerns.

3. Noise pollution may also hinder cognitive ability and focus, especially in youngsters and the elderly.

1.6.2 Methods to reduce noise pollution:

Several solutions may be done to reduce noise pollution from roadway tyre movement:

1. **Materials and road design:** Reduce noise levels by using quieter surfaces for roads, such as low-noise asphalt.

2. **Speed limits:** Enforcing and implementing speed restrictions can reduce the amount of noise, as noise levels rise dramatically with greater speeds.

3. **Noise barriers:** Build sound barriers alongside roads in residential areas to reduce noise's influence on surrounding populations.

4. **Regulations for cars:** Promote the adoption of quieter tyres and vehicles that fulfil noise emission limits.

5. **Road maintenance:** Repair and maintain roads on a regular basis to decrease tyre noise generated by surface defects.

6. **Land use planning:** Address the impact of noise in urban planning through reducing the building of residential zones near loud roadways.

It is feasible to lessen the impact of sound pollution generated by tyre movements on highways and enhance the overall standard of life for individuals who live near these busy routes by implementing these methods.

1.7 Reduction of noise pollution by porous pavement:

Porous pavement is a form of surface that enables water to pass through and soak into the underlying soil. It is additionally referred to as permeable or pervious pavement. It offers an innovative and ecologically friendly method for successfully managing storm water runoff and reducing noise pollution. Here are several ways that porous pavement can assist to reduce noise pollution:

1. **Acoustic properties:** Perforated pavement absorbs sound, which helps to reduce road traffic noise. When cars travel over the pavement's surface, the open spaces throughout the pavement structure capture and disperse sound waves, lowering the level of noise that affects the surrounding environment.

2. **Reduced tyre noise:** When compared to typical asphalt or concrete, the surface roughness of permeable pavement is more uniform and less abrasive to car tyres. As a consequence, tyre movement noise is reduced, resulting in calmer highways.

3. **Removal of puddles and splash noise:** When it rains, regular pavements typically generate puddles and splashing sounds, which add to noise pollution. Water can drain through porous pavement, removing various water-related noise sources.

4. **Rainwater management:** In conjunction with reducing noise, porous pavement effectively manages stormwater by encouraging water infiltration and lowering runoff. During heavy rain events, it helps to prevent the production of loud, streaming water.

5. **Environmental advantages:** Porous pavement recharges groundwater, relieving pressure on rainwater drainage systems as well as preventing water contamination. This ecologically mindful strategy is consistent with the aims of sustainable urban development.

6. **Mitigation of urban heat island effect:** Porous pavement can assist mitigate the urban heat island effect through enabling rainfall to cool the pavement surface and adjacent regions, lessening the amount of heat reflected from typical impermeable surfaces.

Finally, offering permeable pavement as an alternate to typical impermeable surfaces can help to reduce noise pollution and improve stormwater management. By constructing quieter and more efficient streets, this eco-friendly option may improve the overall quality of urban areas.

1.8 Piezoelectric energy harvesting using traffic:

As the globe grapples with the issues of global warming and environmental degradation, finding sustainable energy solutions is more important than ever. On this perspective, piezometric energy harvesting on porous pavement appears to be a viable path for capturing renewable energy from a common urban resource - pedestrian footfalls. Porous pavement, which has empty areas that enable water to seep through the surface, is both a durable paving material and a novel energy source. Piezometric energy harvesting converts mechanical stress created by pedestrian and vehicular traffic movement on porous surfaces into useful electrical energy. This new concept has the ability to completely transform urban energy landscapes, opening the path for ecologically benign and self-sustaining infrastructure. The purpose of this research is to investigate and assess the practicality, efficiency, and sustainability of piezometric energy harvesting in permeable pavement, giving light on its role in promoting environmentally friendly energy alternatives and contributing to the worldwide transition to a greener future.

1.9 Problem statement:

Because of their potential to minimize storm water runoff, improve groundwater recharge, and lessen environmental consequences, porous pavements have attracted increasing attention as environmentally friendly alternatives to traditional impermeable pavements. However, in order to effectively capitalize on the benefits of permeable pavements and assure their broad adoption, many crucial research gaps must be filled. Via a series of experimental experiments concentrating on various new additives and mix designs, this thesis attempts to completely study and optimize the engineering attributes as well as the performance of porous pavements.

The first research attempt attempts to improve the strength and permeability of permeable asphalt pavement under medium traffic circumstances. In order to maintain the pavement's permeability, the research intends to assess the impact of crumb rubber as an additional material on the pavement's structural properties.

In the second study, the engineering characteristics of pervious concrete are examined by partially replacing the cement with Ground Granulated Blast Furnace Slag (GGBS).This study will provide important information on the mechanical qualities, resilience, and overall efficiency of pervious concrete mixes, including GGBS.

The third research project looks into the usage of Low-Density Polyethylene (LDPE) in permeable bituminous pavement as a replacement technique for successful groundwater management. The study will assess the structural behavior as well as the permeability of the LDPE-modified pavement in terms of storm water runoff management and groundwater recharge.

The fourth research study looks at the structural behavior of porous asphalt mixes including slag from steel production as a partial substitute for traditional stone aggregate. The study's goal is to learn about the effects of steel slag on pavement durability, resistance to fatigue, and long-term performance.

The fifth research project investigates the influence of varied coarse aggregate shapes and sizes on the characteristics of porous concrete. The project attempts to optimize the design of permeable concrete mixes to obtain desirable permeability, strength, and resilience by experimenting with various aggregate configurations.

The sixth research project investigates the use of permeable asphalt materials in road building to reduce automobile noise. The study's goal is to assess the sound absorption capacity of permeable asphalt roadways and their usefulness in reducing noise pollution in metropolitan areas.

In the end, the seventh study concentrates on the collection of piezoelectric energy in porous pavements. The project seeks to examine the viability and effectiveness of this method for generating electrical energy while contributing to the environmental sustainability of the road infrastructure by harvesting mechanical energy that is generated by automobile and pedestrian activity on porous surfaces.

This thesis seeks to deliver helpful insights and practical recommendations for the development, construction, and installation of permeable pavements as environmentally conscious and environmentally friendly infrastructure solutions.

1.10 Objectives of the research:

Based on the research gaps and problem statement, the primary aims of the study are-

1. To study the structural and permeable properties of porous bituminous mix using LDPE coated coarse aggregate.
2. To improve the strength of the porous asphalt concrete pavement made with crumb rubber modified mix using nano-silica as a supplementary material.
3. To investigate the performance of porous asphalt mix with steel slag used as partial replacement of coarse aggregate.
4. To assess the engineering properties of pervious concrete with GGBS as a partial replacement of cement.
5. To investigate the viability of porous pavement in road construction for the reduction in traffic noise.
6. To check the effect of shape and size of coarse aggregate on the porous concrete.
7. To investigate the viability of using piezoelectric material to generate electricity while people are walking on a footpath.

1.11 Scope of the work:

The scope of research on porous pavement are as follows:

1. **Comparative evaluation:**

• Conduct a comparison of the several types of additives utilised in the research (crumb rubber, GGBS, LDPE, and steel slag) to find the most effective and sustainable solutions for enhancing the durability and efficiency of porous pavements.

• To discover the best elements and mix designs for certain traffic and environmental circumstances, compare the technical attributes as well as long-term reliability of multiple porous pavement combinations.

2. **Evaluation using multiple criteria:**

• Conduct a multi-criteria assessment of all the different porous pavement elements and designs, taking into account characteristics such as permeability, different strength parameters, resilience, effect on the environment, and economic feasibility.

• Create a decision-making framework to aid in the prioritisation of material selection along with design combinations based on the project's particular needs and sustainability goals.

3. **Field monitoring as well as performance assessment:**

• Conduct field evaluations of different permeable pavement installations to evaluate their effectiveness in real-world situations.

• To validate the conclusions from laboratory tests and simulations, collect data on structural behaviour, permeability, storm water management efficiency, as well as additional performance indicators.

4. **Porous Concrete mixture optimisation:**

• Concentrate on optimising the design of the mix of permeable concrete by taking into account the impact of various coarse aggregate sizes and shapes on its structural integrity.

• Propose a porous concrete mixture that is optimised for particular purposes and traffic loads, balancing permeability, strength, and durability.

6. **Construction of sustainable roads:**

• Extend the research on the use of permeable asphalt material in constructing roads to incorporate additional environmentally friendly practises and resources for a more holistic approach to environmentally conscious road construction.

• Investigate the use of porous pavements in conjunction with other environmentally conscious innovations such as harvesting of rainwater and green infrastructure.

7. **Innovations in energy harvesting:**

• To maximise energy conversion efficiency, further research will explore the possibility of piezoelectric power generation in permeable pavements by optimising the design and positioning of piezoelectric devices.

• Investigate alternative energy harvesting methods, such as solar or kinetic energy, that may be integrated into porous pavements to improve sustainability and self-sufficiency.

1.12 Organization of the thesis:

The thesis is divided into eleven chapters, **Chapter 1**, is an introductory chapter that provides an overview and background of permeable pavement, its environmental conscious construction, the implementation of alternative materials, as well as its influence on noise pollution, as well as the problem statement, research objectives, along with scope for future research. **Chapter 2** provides a comprehensive review of the literature on various aspects of permeable pavement, such as the implementation of polymeric waste materials, noise from traffic, coarse aggregate shapes and sizes, GGBS in the mix of concrete, permeability, and the use of piezoelectric energy harvesting, as well as an overview of the literature along with identification of research gaps. **Chapter 3** goes over the materials needed for porous pavement studies, such as aggregates, bitumen, additives made from chemicals, GGBS, cement, and crumb rubber, as well as the approach for using these materials in various scenarios such as reducing noise, energy harvesting, and testing, as well as final thoughts and statistical analysis. **Chapter 4** discusses the characterisation of permeable bituminous concrete utilizing LDPE coated coarse aggregate, including concept and design principles, materials, and technique. It contains studies including the Marshall mix design, permeability testing, and indirect tensile strength testing, as well as results and debates, before finishing with general findings and conclusions. **Chapter** 5 investigates the use of crumb rubber to improve the strength of porous asphalt concrete. It describes the goals, materials, and technique, as well as sample preparation including the Marshall mix design. The chapter provides and discusses the findings of numerous assessments, such as permeability including indirect tensile strength, and finishes with a summary of the test results, future scope, and general conclusions. **Chapter 6** investigates the structural behavior of a porous asphalt mixture incorporating steel slag to replace natural stone aggregates partially. It describes the significance and aims of the study, as well as the experimental program, materials utilized, and technique, which includes the Marshall mix method, permeability test, as well as Cantabro abrasion test. The chapter includes the findings and conversations that lead up to the general conclusions. **Chapter** 7 investigates the engineering properties of pervious concrete when Ground Granulated Blast Furnace Slag (GGBS) is used as a partial replacement for cement. It contains information on ingredients, mix proportioning, sample preparation, technique, and concrete testing. The chapter includes findings and conversations before concluding with conclusions and future scope. **Chapter 8** investigates the use of permeable asphalt material in road building to minimize automobile noise. It discusses porous asphalt pavement, the research location, and the materials and technique employed, as well as the design of the noise trailer, data collecting, and laboratory testing. The chapter includes findings and debates before finishing with conclusions and recommendations for further research**. Chapter 9** investigates the effects of the shape and size of coarse aggregate on porous concrete. It starts with a broad overview of permeable concrete and its benefits, then moves on to a description of the study's aims and scope. The chapter then looks into the materials and procedures employed, such as mix proportioning and concrete testing. It contains the findings as well as the outcomes and debates**. Chapter 10** explores energy harvesting from pedestrian movement using piezoelectric materials. It describes the general context, study objectives, piezoelectric characteristics and theory, pedestrian energy harvesting methodology, including piezoelectric harvester modeling and sensitivity evaluation, as well as concludes with findings, the limitations of the study, along with future research opportunities. Chapter 11 presents the findings of various studies on various aspects of porous pavement and its applications, such as bituminous pavement with plastic modification, crumb rubber modification, coarse steel slag aggregate in asphalt pavements, GGBS in pervious concrete mix, noise pollution control using porous asphalt, aggregate shape and size influence, and piezoelectric materials for electricity generation on footpaths. The chapter also includes recommendations and ideas for future research projects. A list of **References** has been presented at the end of the thesis.

CHAPTER-2

LITERATURE REVIEW

2.0 General

The goal of this chapter is to compile the existing research on the viability of using waste materials to build porous layers of concrete and asphalt as well as piezo crystals to capture energy from the road surface. A variety of waste materials, such as crumb rubber, low-density polyethylene, GGBS, steel slag, and coarse aggregate in a variety of sizes and forms, are investigated for their physical, mechanical, and durability properties. The literature on the utilization of waste materials is thoroughly reviewed for this. Additionally, research on piezo harvesting methods is done to capture the energy emitted from the pavement surface. A comprehensive state-of-the-art has been gathered. To organize the study content properly and establish review objectives, the entire body of literature is carefully reviewed.

2.1 Review on the use of polymeric waste materials in Porous Pavement:

Putman and Neptune (2011) discussed in the study the comparison among several permeable ways for creating test specimens for concrete in an effort to create specimens with characteristics resembling those of stationary pervious concrete pavement. On three separate paving projects, pervious concrete was used to cast slabs and cylinders using various techniques. On the basis of infiltration rate, density, and porosity, cast specimens were compared to pavement cores. The standard Proctor hammer produced qualities that were close to those of the in-place pavement and had the least range of outcomes among the cylinder consolidation techniques that were examined.

Brown and Borst (2014) examined the Surface Infiltration Testing Methods in Permeable Pavement systems. The ASTM technique for calculating the rate of infiltration of stationary permeable concrete offers no direction on where to conduct tests or how the data should be interpreted in order to determine how well the surface is doing and whether any upkeep is necessary. Since the ASTM approach was created primarily for pervious concrete, more investigation is required to discover whether it can be used for other forms of permeable pavement. Over the course of the nearly three years of surface infiltration testing, two strategies were used to choose test sites: monthly testing at randomly picked spots and quarterly testing at fixed locations. For each type of pavement, the infiltration rates were substantially different. Maintenance has not yet been required despite infiltration declining in places directly underneath impervious asphalt driving lanes and to a higher extent where disturbed soil was present after nearly three years of use. The clogging process was said to be responsible for the longevity. Runoff moves solids up to the permeable pavement surface's upgradient edge, where they are filtered and gathered when runoff infiltrates. The strategy of choosing a random place over the entire region often results in the majority of locations being in an untouched area when surface congestion proceeds from the upgradient edge. The infiltration rate did not vary significantly enough to indicate that the entire surface required maintenance. The findings suggest that the ASTM C1701 approach may be suitable for PICP; further research is required for PA. Future infiltration tests are advised to carefully choose fixed test sites based on anticipated obstruction tendencies. Additionally, since less water is required, more tests can be carried out strategically throughout the pavement surface, helping to pinpoint the regions of clogging.

Gaedicke et al. (2016) looked into how permeable concrete cylinders and cores' crushing and splitting properties correlated. Using three different aggregate kinds, paste, and slag contents, sixteen combinations were created. Tests on both cast cylinders and cores showed that the link between splitting tensile strength and crushing strength depended on the kind of aggregate. The paste and slag contents of the combinations had little to no impact on the link between splitting tensile strength and crushing strength. Additionally, it was discovered that the core specimens' splitting tensile strength against strength curve was steeper than the average curve for the entire specimens, demonstrating that the equation for placed cylinder samples is off by 7 to 13% for crushing strengths of 10 to 20 MPa, respectively, when determining the core splitting tensile strength. This study offers formulas to compare the crushing strength and splitting tensile strength of cast or cored pervious concrete cylinders.

Chandrappa and Biligiri (2016) studied that permeable concrete has lately grown in popularity as a paving material for low-volume road applications because of its positive environmental properties. This study assesses the most recent developments and state-of-the-art in connection to earlier concrete research and behaviours. A review of the multiple research examinations into the physical, hydrological, and durability properties of pervious concrete has been done. Pollutant removal from storm water has been demonstrated to be successful with pervious concrete. Field research on a few test sections and in-service pervious concrete pavements have both been covered. There has been a review of methods for increasing the drainage efficiency of pervious concrete pavements. Pervious Concrete's analysis of life cycle costs has been mentioned. Due to pervious concrete's increased use in the pavement industry as a result of its many benefits, there is a huge need for additional research to better understand the substance and make it a workable, sustainable highway material in the years to come.

Ma et al. (2018) examined the effects of various additions on the porous asphalt mixture. This project's goal is to explore methods for enhancing porous asphalt's strength and durability through laboratory testing. Three different binders were used to make porous asphalt specimens. The porous asphalt was mixed with fiber, hydrated lime, and DBS polymer, among other additions. Different tests were performed in the lab. HVB is the ideal type of binder for porous asphalt since extensive laboratory research has demonstrated that it may greatly enhance the performance of porous asphalt. The kinetic viscosity and softening point of the binder can both be significantly raised by the DBS polymer. By adding DBS, porous asphalt becomes more resistant to rutting but less durable and tolerant of low-temperature cracking. Porous asphalt's hardness and resilience to low-temperature cracking can be improved with fiber. An effective method to assess the resilience of porous asphalt is the cantabro test, as opposed to the freeze-thaw cantabro test. Except for permeability, the additives significantly affect the overall performance taken into account in this investigation.

Khilari et al. (2017) investigated the effect of crumb rubber content and size dispersion on the functionality of porous asphalt matrixes. Using a dry technique, different ratios of crumb rubber's grain size and concentration were added to the bituminous concrete mixture. It was observed that whereas using crumb as a modifier improves the Marshall Stability value of the matrix and reduces the penetration value of bitumen, it reduces the air void in the mix, thus reducing the permeability of porous asphalt. The reduction in drainage property isn't significant enough as compared to the increased strength of the mix. The observations gathered allow for the safe conclusion that crumb rubber-modified porous asphalt is suitable for usage in locations with low to moderate traffic volumes.

Mishra et al. (2015) studied the improvement in strength and stability of bituminous mix by using plastic-coated aggregate, thus finding a safe way to dispose of the plastic waste and providing a solution to environmental contamination as well. In this study, a dry process is used for mixing waste plastic into the matrix. Marshall Specimens were prepared using 80/100 grade bitumen, with bitumen content ranging from 4–6% by weight of aggregate. The waste plastic contents used ranged from 0–16% by weight of optimum bitumen content. Using waste plastic allowed for a significant improvement in aggregate properties as well as the properties of bitumen. Along the way, the scope provided by this study for using waste plastic in the asphalt mix paves the way for their safe disposal and also contributes to the construction of green roads.

Sun et al. (2018) investigated the use of geopolymers and alkali-activated slag in the production of pervious concrete. With its networked void structure, pervious concrete provides environmentally friendly stormwater management. Alternative cementation materials, including alkali-activated slag and geopolymers, have attracted interest because of their potential to improve the functionality and sustainability of pervious concrete. These alternate materials can help existing concrete be stronger, more resilient, and more sustainable. The use of industrial wastes, improved mechanical qualities, and reduced environmental impact are only a few benefits of alkali-activated slag and geopolymers. To improve mixture proportions, curing conditions, and the long-term performance of pervious concrete built with alkali-activated slag and geopolymers, additional research and experimental studies are required.

Shukla and Gupta (2019) studied developing pervious concrete with desired physical and mechanical properties for concrete flatwork applications. Cement content is a crucial factor in designing pervious concrete. Cement slurry, which forms when there is too much cement and settles, can render the concrete base impermeable. To prevent water loss, pervious concrete should be thoroughly mixed. For large-scale laboratory work, steel or iron mixing trays can be utilized, whereas a concrete mixer is advised for heavy concreting. Avoid using vibratory compaction techniques like table vibrators since they can cause cement slurry to settle gravitationally and render the specimen impermeable. Only manual compaction is advised. To prevent bug holes when oiling the molds, don't apply too much oil to the surface. The oil used should be non-sticky and have lubricating qualities. It is advised to use black oil in automobiles. The specimens with the maximum cement permeability (484 kg/m^3) were made from the three different mixes with the three different cement proportions (479 kg/m^3, 446 kg/m3, and 384 kg/m^3). Three mixtures with varied sand contents (0%, 15.02%, and 30.22%) were made with 384 kg/m^3 of cement. While the third blend was impermeable, the previous two mixtures showed good permeability. Due to Mix 1's lower compressive strength and greater permeability, the second mix with 15.02% sand is advised.

Chen and Yang (2020) examined the design, build, and performance aspects that could maximize the benefits and minimize the drawbacks of using PAC mixes. With a focus on the use of PAC in agency practices, a comprehensive assessment of the global literature on PAC uses was done, and PAC design from around the world was assessed. A recommended practice for PAC choice of materials and design, as well as a suggested practice for PAC construction and maintenance, were highlighted based on an examination of the review's findings. The PAC drainage should be carefully evaluated, and there should be enough asphalt in the mix to enhance the functionality of the pavement's outer layer. The long-term durability of the PAC mix depends on a correct binder content stabilized by additives like fibers and polymers, which is necessary to maintain a sufficient film thickness.

Deo and Neithalath (2011) offered details on the compressive behavior and proportioning of pervious concrete mixtures. It covered how crucial pore size, cement paste quantity, and porosity affect pervious concretes' ability to withstand compression. Additionally, it underlined the linear connection between compressive strength and energy absorption in concrete specimens with pervious surfaces.

2.2 Review on Traffic Noise in Porous Pavement

Weiss et al. (2019) focused in their study on the fact that permeable pavements are already existing in northern America, most of which are found in parking lots, and in commercial areas they are found in slow and moderate traffic. These are a few of the significant findings they made: (1) Full-depth permeable pavements have a top layer of porous wearing course that can hold runoff until it seeps into the surrounding soil or is conveyed downstream by a drainage pipe, as well as aggregate layers with up to 40% void spaces. There are regional differences in layer thickness, particle size distribution, and the use of geotextiles. (2) No established common structural design methodology exists for all varieties of permeable pavement. (3) The most common type of hydraulic design is based on calculating the subbase's infiltration potential and providing enough space for the design storm. (4) The removal of surface debris must be done on a regular basis to keep a permeable pavement system functioning properly. Typically, vacuuming and/or water pressure washing have been proven to be efficient (5) It has been demonstrated that using permeable pavement for highway shoulder retrofits is both technically possible and potentially economical. (6) Improved skid resistance, quicker snow and ice melting, and load resistance are some benefits of permeable asphalt and concrete pavement. (7) Subpar mix design, subpar construction techniques, and subpar maintenance contributed to numerous permeable pavement failures.

X. Hu et al. (2019) studied the impact of activated carbon on the optimal asphalt composition, technical features, and filtration properties of Porous Asphalt Concrete (PAC) in order to improve the efficacy of pavement runoff filtering. According to extensive laboratory experiments, high activated carbon absorptivity and specific surface area increase the porous asphalt mixture's optimal asphalt content. By enhancing the bonding properties of the aggregate and asphalt binder, activated carbon helps the porous asphalt mixture's moisture stability. The stiffness of activated carbon and the softening effect of high asphalt concentrations both have an impact on PAC strength. The rate of pollutant removal and the pH of the runoff solution changed remarkably little over the monitoring period in this study's filtration test. These characteristics have a major influence on the filtering efficacy of PAC; it is recommended to employ a PAC layer with a 6 cm thickness and an 18% air void ratio.

Alber et al. (2018) examined the connection between soiling occurrences and the acoustic characteristics of porous asphalt. On the physical and functional properties of PA, it is claimed that the void content as well as the pore structure play a significant role. The air void's microstructural components may lack steady, temporal, and spatial properties. The change in porosity structure produced by soiling and clogging is commonly acknowledged to be quantifiable and testable. This study devised artificial soiling tests (AST) to imitate the soiling process that happens when PA is used. The soiling mechanism is studied using light-optical microscope photos of thin slices and images from scanning electron microscopy. Acoustics enables a thorough investigation of the effects of key characteristics, such as structural components and tortuosity, on the structure and acoustics of pores, as well as modifications brought on by soiling mechanisms. Flow resistivity values were found to be greater in finer and thinner PA structures than in coarser and thicker ones.

Zhang et al. (2018) examined the effectiveness of using red mud as a filler to enhance porous asphalt. Its porosity determines the benefits of porous asphalt pavement for the environment, including water filtration, noise reduction, and surface runoff drainage. The results of the tests and data analysis allow for the following conclusions and recommendations: Adding filler to asphalt can increase its performance at high temperatures. Using red mud as a filler can significantly boost the percentage of asphalt recovery. The reveling resistance of the PA combination has grown dramatically as FB has increased. But a higher FB will lead to poorer permeability and a greater amount of asphalt. The results of this little study indicate that 0.9 FB is the ideal FB when accounting for the ravelling resistance performance, permeability, and economic benefit of the PA combination. Red mud performs better than PA mixed with lime powder when the FB is 0.9 in terms of resistance to rutting, wetness, ravelling, and aging. To improve specialized PA performance, red mud, a sort of solid waste created by the aluminum industry, can be used as a filler as opposed to limestone powder.

Wu et al. (2020) examined the mechanical performance of porous asphalt when exposed to moisture activities and laboratory aging. This work has primarily focused on the mechanical performance of porous asphalt mixtures under laboratory aging and moisture activities. Due to its relative higher void content, porous asphalt pavement experiences more severe aging and waterinduced performance decreases than low-void asphalt pavement. This work developed a novel coupling treatment delivery system for asphalt mixtures under various aging and moisture scenarios. The corrosion and fatigue resistance of the treated samples were assessed using the findings from the dynamic stability and three-point bending beam fatigue tests. Using the variance matrix, the combined effects of lab aging and moisture were also investigated. The results demonstrated that aging initially had a favorable effect on the rutting resistance of asphalt mixes; however, further hardening will cause the adhesion between bitumen and aggregates to degrade. The presence of water will, to some extent, lessen the effects of aging due to oxygen depletion and the ability to change temperature, but the consequences of aging do not significantly alter the function of moisture. The dynamic stability of asphalt mixtures steadily declines with a particular moisture content. In the long run, dampness has very little bearing on how well a person handles fatigue.

Chavanpatil et al. (2018) studied the durability, environmental effect, maintenance, and hydrologic considerations of a full-depth Porous Asphalt (PA). As per NAPA (2008), the minimum thicknesses of the wearing course to be maintained are 2.5", 4, and 6" for parking lots, residential traffic, and heavy traffic, respectively. The model they developed with a drain-out system consists of (i) Porous Asphalt consisting of asphalt binder of PG 70-28 and stone aggregate passing 34" and retained on 12" and fine content between 16% and 22%, (ii) Checker/ filter course of 12" crushed aggregate, (iii) Railroad ballast of 2-212" size crushed stones, (iv) Uniformly graded clean crushed stones with 40% void and non-woven Geotextile sheet. Using their model, they found success in increasing water storage capacity, noise reduction due to vehicular operation, increasing capacity in rainwater harvesting and therefore increasing GT recharge, and also reducing overland runoff depth. It is also observed that porous pavement is economically very efficient as fewer earthworks are needed as compared to conventional roads because it fits right into the topography and also allows the site planner to manage storm water in an environmentally friendly way.

Teti et al. (2020) simulated the soundproofing capabilities of recently installed low-noise pavements. The current work presents a novel approach for modeling the CPX of newly constructed low-noise roads using only data that was provided to the designers before being laid or that was simple to obtain through coring tests, including the grade curve, fractal dimensions, binding agent content, air spaces, and gaps in substance stones. Two models were developed to be able to predict CPX levels using two distinct tire/road noise separations. The initial model divides contributions into high and low frequencies, whereas the following model employs a three-band model and also accounts for noise around 1 kHz independently. Both models can predict the acoustic characteristics of recently installed low-noise motorways using an alternative route mixing criterion at various harmonic spectra. The three-band model has a reduced RMSE.

Zhang et al. (2020) studied to identify an optimal low-noise pavement pattern for efficiently reducing tire-pavement noise in lengthy motorway tunnels. Some of the key metrics that were examined include the weighted pressure of sound level, pitch, sideway force factor, and the actual unit cost of producing a single texture. The OBSI system detects sound signals at the tire-pavement interface, independent of any adjacent sources. The road tunnel provides an unfavorable acoustic environment, according to the research. The sound of tires on the pavement within the tunnel is around 20 dB (A) louder than the surrounding normal areas, depending on whether it is asphalt or cement concrete. In addition, a horizontally equidistant groove with a high center spacing of 25 cm is considered a wonderful approach from an economic standpoint since it prevents automobiles from rolling to the side while minimizing roaring noise. Also take note that the area close to the tunnel entrance is a transition area between the lowest area of skid resistance and the tire-pavement noise region. This part and the moist area within the tunnel can still be thought of as appropriate candidates for the crosswise unequal spacing groove. Another noteworthy finding is that there is no obvious correlation between tire-pavement noise and sideway pressure factor, regardless of how smoothly the grooves are made. This enables the creation of a quieter pavement surface without compromising skid resistance.

Callai and Sangiorgi (2021) examined Road Pavement Acoustic and Skid Reduction Technologies. The literature offers techniques for creating a pavement surface layer that produces repeatable outcomes. Asphalt mixtures include a variety of solutions, most of which are the result of years of research and study. They all manage the surface's macro and microtexture, yet they all employ various strategies to be effective for noise and friction. In order to solve noise and skid resistance problems, multiple factors are addressed in revolutionary paving options using synthetic aggregates rather than natural ones.

Mikhailenko et al. (2020) studied assessment methods and Low-Noise pavement technology in their work. In both lab and field settings, test procedures for assessing the acoustic characteristics of asphalt pavements are examined. The most popular pavement acoustics field test is the Close-Proximity (CPX) method, which follows in accordance with the Statistical Pass-By (SPB) and On-Board Sound Intensity (OBSI) procedures. The CPX is more practical, even if it seems like the SPB is the most detailed method. Impedance tubes for absorbing sound as well as laboratory pavement noise simulators are two techniques for testing the acoustical qualities; nevertheless, mainly the larger drum techniques can simulate in-situ conditions. Techniques for non-acoustical noise-relevant properties such as surface roughness, porosity, and airflow resistance were studied as well. It was discovered that enhancing surface roughness at the macroscale was crucial for lowering tire and road noise. The most consistently low-noise pavement kinds are made of porous asphalt concrete (PAC) as well as its derivatives, albeit with certain maintenance and durability issues. Finally, numerous approaches for predicting acoustical quality were addressed.

Awwal et al. (2020) analyzed the levels of highway noise on concrete and asphalt pavements as well as the applicability of the current traffic noise forecast models. The results show that traffic noise normally ranges between 79 and 89 dBA, and the bulk of the greater noise occurs between the peak hours for asphalt pavement and the off-peak hours for concrete pavement. The Penang noise model's pattern was found to be the most similar to the observed noise when five traffic noise models were contrasted with the actual noise. Regression modeling was used to create a traffic noise model that can predict the noise generated by different types of pavement in different traffic conditions. It was discovered that all traffic noise models could accurately forecast the current level of traffic noise. This leads to the conclusion that a fresh road noise model is needed for a specific condition in order to improve traffic noise prediction. Under different traffic circumstances, the pattern of traffic noise on different types of pavements is not the same.

2.3 Review on the influence of varying size and shape of coarse aggregates

Ibrahim et al. (2014) investigated the hydrological and mechanical qualities of pervious concrete constructed using Portland cement. In this study, researchers used one or two aggregate sizes to investigate how the size of the course fraction, the w/c ratio, cement content, and volume of coarse aggregate influenced the compressive strength, porosity, and permeability of test samples. They discovered that employing aggregates with no more than two sizes had a substantial impact on hydrological characteristics like porosity and permeability. Additionally, they noticed that the porosity and consequently the permeability of PCPC decrease as its density rises, although the crushing strength of test specimens increases. A maximum crushing strength of 6.95 MPa was reached using 9.5 mm single aggregate with a cement concentration of 250 kg/m^3.

Cosic et al. (2015) studied how aggregate size and kind affected the previous concrete's characteristics. A conventional dense concrete mix and, moreover, four pervious concrete mixtures (30:60 or 60:30) with a range of aggregate types and ratios of 4–8 millimetre to 8–16 millimetre aggregate fractions were developed. The research revealed that increasing the amount of small aggregate fractions (4–8 mm) in concrete mixtures produced denser materials with improved flexural strengths. A higher overall porosity is reached when comparing pervious concrete with dolomite aggregate to pervious concrete with steel slag aggregate.

Bonicelli et al. (2015) investigated the impact of varying compaction energy levels and examined the impact of adding fine sand to various pervious concrete compositions. They examined the connections between void content, trainability, stiffness, strength, particle loss, and bulk density and proposed that small additions of finer sand (about 5% of the overall aggregate weight) could enhance the physical and surface properties of permeable concrete mixtures while lowering trainability.

Torres et al. (2015) examined the impacts of cement concentration, aggregate size, and compaction technique to relate the thickness of the cement paste to the performance of pervious concrete. Because permeability also depends on the surface area, size, and distribution of the voids, a material's permeability does not always equate to its porosity. This study establishes a link between crucial pervious concrete properties such as porosity, permeability, crushing and tensile strength, and cement paste thickness. According to the findings, a thicker cement covering will result in less percolation because it reduces porosity, but it may also improve other desirable mechanical qualities like permeability and compressive or tensile strength.

Grubea et al. (2018) examined the mechanical and hydrological properties of six combinations of single-sized pervious concrete, which are made from dolomite, dia base, and steel slag from garbage dumps in Croatia. The hydrologic properties of permeable concrete were computed using its drainage capacity. The suitability of using permeable concrete as a surface layer for pavement construction in the European region was evaluated by comparing its achieved mechanical attributes with those required for such a purpose. The findings showed that dia base was the best aggregate type for producing permeable concrete from a hydrologic perspective because of its sharp grain edges that allow water to move through the pore system efficiently.

Yu et al. (2019) emphasized the importance of aggregate size in determining pervious concrete's compressive strength. Well-graded aggregate mixtures with a range of sizes promote mechanical interlocking, enhance void structure, and contribute to improved strength. However, the relationship between aggregate size and compressive strength is complex and influenced by factors such as aggregate distribution, void content, and maturity of the concrete. Further research and experimental studies are necessary to optimize aggregate size selection and achieve the desired performance of pervious concrete in various applications.

Rahangdale et al. (2017) studied pervious concrete. In pervious concrete, only one size of coarse particles is often used. According to IS code 10262:2009 for mix design, coarse aggregates measuring 16 mm are used for pervious concrete, and the strength of the concrete improves as the coarse aggregate size drops. Styrene Butadiene is typically used as a water-reducing agent in pervious concrete. Binding materials are Portland pozzolana cement of OPC grade 53. The findings showed that the crushing strength of permeable concrete was considerably impacted by the concrete's porosity, age, binding substance (kind of cement), test specimen shape, and size. Porosity and crushing strength are inversely related; as a result, porosity decreases as crushing strength rises. Concrete with pores is not appropriate for heavy-duty roadways. Due to the material's porosity, wet cement falls to the bottom when there is more water present than is necessary. Porosity decreases when more tamping is required. The porosity of porous concrete affects its permeability. Compared to other types of roadways, permeable concrete has greater friction.

Gaedicke et al. (2016) described how to correlate the split tensile and crushing strengths of cylinders and cores in permeable concrete. It addressed the impact of porosity variation between split tensile and crushing strength samples and examined the relationship between split strength and crushing strength of permeable concrete. The effects of aggregate type, paste content, and sample type (core versus high-density lab cylinder) Tensile tear strength, and crushing strength correlation formulas are put forth and contrasted with those found in the literature.

Cui et al. (2017) investigated the connection between the strength and permeability of permeable concrete. Its aim is to address the limited research results on quantitative relationships between permeability and strength qualities of permeable concrete that may be used for mix design as well as optimization. A series of laboratory investigations show how the w/c ratio, a/c ratio, and porosity affect the strength and permeability of water-permeable concrete. The findings indicate that strength and permeability are negatively correlated, with increased strength resulting in reduced permeability. In addition, a modified permeability test method considering existing limitations is proposed.

Sir and Setiana (2020) researched sidewalks in large cities and small towns, which play a crucial role in the design of urban street plans. It used descriptive qualitative methods conducted by collecting data from literature studies supporting the porous concrete theory. Based on the data obtained, the compressive strength of AAC is dependent on aggregate size, cement moisture coefficient, and the number of additives used, with the highest compressive strength found in the study being 153 kg/cm^2, which is equivalent to 1 sq. meter. It can supply 69 to 113 liters per minute of water. Aerated concrete has a high tensile strength in bending and low compressive strength, so it does not meet the pavement standards for the main body of the road. It can only be used as an open parking lot. Curbside or pedestrian areas are allowed.

2.4 Review on GGBS in Porous Concrete Mix

Hassan et al. (2016) investigated the pervious concrete's mechanical and transport characteristics with GGBS as a 50% substitution. They also looked into the possibility of dust-exposed pervious concrete clogging. The findings showed that as porosity rose, compressive and tensile strength decreased. Short-cut polypropylene fibers were added to the mixture. In low-porosity concrete, the fiber addition worked well. Additionally, it was discovered that permeability was negatively correlated with aggregate size and positively correlated with porosity. The water flush maintenance procedure was able to restore the concrete's permeability after 40 years of simulated exposure to dust. Since it reduces prices, the heat island effect, and embodied energy, pervious concrete, including GGBS, is a more environmentally friendly paving solution than conventional Portland cement concrete.

Ali et al. (2019) analyzed the substitution of some of the cement in concrete with Fly Ash and GGBS. Here, the aim is to address the environmental concerns associated with increased cement demand. Various replacement percentages (0% to 30%) of GGBS and Fly Ash were tested at different curing periods. Tests were conducted on M25-grade concrete samples at 3, 7, 14, and 28 days of curing. The concrete's workability, assessed through slump, compaction factor, and Vee-Bee tests, along with its compressive strength, was evaluated. For all mixes, the cement-to-water ratio was held constant at 0.47. The findings show that prolonged curing durations result in increased workability and compressive strength. The replaced concrete exhibited enhanced workability, achieving a 30% higher slump value in contrast to the control mixture (SF0). Additionally, the compressive strength of the SF9 mix with 30% replacement was significantly higher than SF0 by 26.30%. Workability initially increased with replacement percentage but decreased partially after reaching an optimum limit. Increasing GGBS and Fly Ash content reduced workability while maintaining the same water-cement ratio (w/c). Optimal workability was observed at a 15% replacement percentage, providing a 30% improvement compared to the control mix. Concrete specimens with 30% replacement (SF9) surpassed SF0 and attained the greatest compressive strength of 33.45 MPa.

Suda et al. (2019) carried out an experimental investigation to determine the appropriate use of GGBS and nano silica to to enhance the concrete's strength characteristics. GGBS and nano silica are commonly used supplementary cementitious materials that offer numerous benefits, including improved strength, durability, and sustainability. In order to understand the impacts of adding GGBS and nano silica to concrete, previous research has been analyzed. This paper also considers the best way to use these components. The use of nano silica and GGBS individually or in combination results in increased compressive strength, flexural strength, and durability properties. The synergistic effects of these materials contribute to the improved performance and sustainability of concrete structures. Exploring the long-term performance and economic viability of these materials in various concrete applications will require more investigation and testing.

Bhaduria and Singh (2021) focused on the comparison research, which examines the utilization in no-fines concrete of fly ash and GGBS as partial cement replacements. No-fines concrete, which lacks fine aggregates, has benefits including improved porosity, a lighter weight, and better thermal insulation. Using cement made of GGBS and fly ash substitutes in no-fines concrete has drawn attention because of its potential to increase the material's performance and sustainability. It draws attention to a comparison study on the usage of GGBS in place of cement in no-fines concrete and fly ash. This additional cementitious material's inclusion improves the physical characteristics, durability, and sustainability of no-fines concrete. GGBS and fly ash contribute to enhanced strength characteristics, reduced permeability, and improved long-term performance. Further research and experimentation are necessary to optimize the mixture proportions, curing conditions, and long-term behavior of no-fine concrete incorporating GGBS and fly ash.

Oner and Akyuz (2007) discussed the impact of concrete's compressive strength, and the appropriate level of GGBS was studied in a lab experiment. The partial replacement method was used to incorporate GGBS into all of the mixtures. Four groups of 32 permutations were made, with the amount of binder in each group being different. Eight mixes with cement contents were made as control mixtures. By deducting 30% of the cement content from the control concretes, initial dosages were established for each group. The test findings demonstrated that as the amount of GGBS is increased, the crushing strength of concrete mixtures containing GGBS increases. The addition of GGBS does not increase the crushing strength after an optimal point, or at roughly 55% of the total binder concentration. This can be explained by the unreacted GGBS used as a filler in the paste.

El-Hassan and Kianmehr (2018) investigated the use of GGBS in permeable concrete pavements to reduce road runoff and improve urban sustainability. This article highlights the benefits of using permeable concrete pavements in urban areas and discusses the challenges associated with their use. Permeable concrete with a 50% blast furnace slag replacement (GGBS) was tested for its mechanical and transport characteristics. Porosity was created using 10 mm and 20 mm open-grain aggregate. Polypropylene short fibers were added in amounts of 10%, 15%, and 20% to the mixture. Permeable concrete's exposure to dust has been investigated. The findings demonstrated that as porosity increased, compressive and tensile strength dropped. When applied to low-porosity concrete, this treatment was effective. Porosity and aggregate size are inversely correlated with permeability. Concrete restoration by washing with water recovers permeability after 40 years of fictitious exposure to dust. In comparison, permeable concrete with GGBS is a more sustainable solution compared to ordinary Portland cement concrete. Sustainable paving solutions that offer cost savings, heat island effects, and energy integration reduce CO_2 emissions by 54%.

Limbachiya et al. (2016) examined the leaching, strength, and durability characteristics of concrete paving blocks combining GGBS and SF. Ternary blends are a reaction to pressure from the economy and the environment to lower the cement content of concrete paving blocks. SF and GGBS were employed as cementitious materials in place of Ordinary Portland Cement (OPC). From an analysis of cement paste cubes, the study reported on the optimal mix. The following day, the manufacturer created the two blends with the highest strength. The study achieved stronger concrete paver blocks than the control mix while successfully reducing the cement content of the blocks by 40%. According to the leaching investigation, mixtures including cement substitutes had increased permeability and absorbed less leachate, but provided satisfactory performance for preventing leachate from reaching ground sources.

Phul et al. (2019) evaluated their work on concrete's crushing strength properties when GGBS and fly ash were used as partial replacements for cement. In this context, environmental concerns have been raised due to the rising need for cement in the construction industry. GGBS and fly ash are used to replace cement with waste. Optimal contents of GGBS and fly ash were evaluated at varying percentages from 0 to 30% for different curing days. Slump, compression modulus, bubbly, and crushing strengths of the replaced concrete were tested. The cement-to-water ratio was maintained at 0.47 for all mixtures. Crushing strength tests were performed on M25-grade concrete with curing times of 3 days, 7 days, 14 days, and 28 days. Results of slump, compressive modulus, and concrete containing GGBS and fly ash showed an increase in Vee-Bee and crushing strength with longer cure times. As a result, it was found that adding GGBS and fly ash to concrete improved its workability and crushing strength, which in turn improved its mechanical properties.

Suda and Rao (2020) investigated the best application of GGBS and nano silica for concrete strength qualities. This study looked at different ways to combine MS and GGBS to create the best ternary concrete mixtures, which were then tested for workability, crushing strength, cleavage strength, and flexural strength. The output shows that the use of mineral additives can produce effective and efficient ternary concrete. Not only does this improve strength properties, but improvements in compressed concrete also improve many other beneficial properties, making it more durable.

Hanumanthappa and Ramya (2023) studied the effect of blended fibers of polypropylene and polyethylene on the early strength and concrete properties achieved. Mixtures of different fiber fractions and amounts of cement partially replaced with GGBS were tested. Results show that the samples made from GGBS containing 15% cement substitute and 3 kg/m^3 fiber have high initial crushing strength, breaking strength, and flexural strength values of 25%, 25%, and 27.5%, respectively, and are durable. It showed significant improvement in characteristics when GGBS was inserted to 30% coverage of cement at both 28 and 56 days.

Mamatha et al. (2018) experimented with replacing some of the cement in stiff pavements with GGBS and flyash. In today's world, when individualism is at its most basic level, the idea of being an advanced nation is taken into consideration. The term "concrete mix design" refers to a system for choosing In order to produce concrete with the requisite features, such as strength, durability, and workability, in an economical manner, it is important to choose the right materials and calculate their relative amounts. GGBS and fly ash are two examples of solid trash produced by various industries. They are therefore viewed as pollutants or wastes because they are readily available, inexpensive, and employed in part-replacement situations. The replacement approach is used in this project. Cement can be partially replaced by GGBS and Fly Ash as an affordable alternative. At 20%, 40%, and 20%, respectively, GGBS and Fly Ash are used to replace cement. M40 is the concrete grade. As a result, the concrete tests were run for 7, 14, and 28 days. For all mixes, the w/c proportion was held constant at 0.45.

Prasanna et al. (2021) examined the durability and strength of fibre-reinforced concrete using GGBS to replace some of the cement. For every tonne of cement produced, almost one tonne of CO_2 was generated during the manufacture of cement clinker. To reduce CO_2 emissions, cement use has to be decreased by the use of alternatives. By-products are used to replace cement in the building industry to improve its strength qualities while reducing pollution and costs. To assess GGBS's efficacy as a cement substitute and to improve the tensile and flexural strengths and functionality of concrete, all tests are carried out in accordance with Indian standard codes. Using concrete specimens that were cast at dates of 28, 90, and 180 days, the strength variations of concrete with and without fibers were examined. Durability experiments, including the absorption of water, sorptivity, and RCPT, were carried out on GGBS concrete without fibers at 28 and 180 days. Concrete's crushing strength is boosted by about 20–20% by replacing up to 40% of the cement with GGBS. Concrete's split tensile and flexural strengths are significantly increased by steel fibers. Split tensile and flexural strengths of SFRC increased significantly when compared to traditional concrete without fibers over a 28- to 180-day period, with values ranging from 19 to 65% and 18 to 74%, respectively. A startling reduction in RCPT, sorptivity, and absorption of water values was observed when the cement was largely substituted with GGBS at 80% of the volume of regular concrete.

2.5 Review on the permeability of porous pavement:

Kayhanian et al. (2019) examined the potential for permeable pavement in storm water runoff control and pollution prevention. High-rainfall sites need a minimum aggregate thickness that is about 50% higher than medium-rainfall locations. The results of the permeability test revealed that permeability measurements could be performed on any type of pavement surface using both the ASTM C1701 and NCAT methodologies. According to permeability studies performed in permeable parking lots, the amount of fine particles (particles less than 38 mm) and the pavement age are two of the most important elements affecting the pavement permeability value. According to the clogging studies, the air gaps of the top surface pavement were typically smaller, which might be an indication of clogging caused by particle buildup. Stresses and the rutting effect, according to HVS testing, can also produce a reduction in the quantity of void space (porosity) in surface pavement, an issue that isn't necessarily caused by particles. Vacuuming can be done as part of normal maintenance to remove the particles that obscure the surface pavement. According to the findings of a controlled laboratory leaching investigation on large areas of open-graded and dense-graded asphalt and concrete pavements, the majority of the concentrations of organic and inorganic chemical constituents produced by specimen leaching were below or within the reporting limit (detection limit). The quantity of pollutants leached is unaffected by temperature. The aging (heat treatment) of the surface pavement materials had no effect on the amount of leached pollutants. Future integrated sustainable mobility systems will feature full-depth permeable pavement (FDPP) in particular. When appropriately constructed, FDPP can be used in place of best management practices (BMPs) to regulate storm water runoff.

Nakanishi et al. (2019) experimented with several mix designs to change the strength and longevity of porous asphalt pavement surface courses. They did this by employing gap-graded aggregate and changing the binder's viscosity, following the process used in Japan. Better mechanical characteristics, effective anti-stripping, and anti-aging features define the improved binder. When exposed to high temperatures, the porous asphalt pavement has a tendency to disintegrate. This is due to the fact that when temperatures rise, mechanical characteristics decrease. The type of asphalt used and the ratio of aggregates in the mix are the main factors that affect how long-lasting and sustainable a porous asphalt pavement will be. The appropriateness of the porous asphalt can be assessed by considering its PG, softening point, viscosity at 60 °C, and other mechanical properties. TPS is a modifier used to improve the penetration grade 60 or 70 qualities of traditional binders. The TPS modifier yields a binder grade that is roughly equivalent to PG82. It takes less than a minute to manually pour it into the pug mill of the asphalt batch mix plant and thoroughly combine it with the porous asphalt mixture. When viscosity reaches its softening point at 60 °C and complies with Japanese standards, the TPS-modified asphalt performs better. A gap between the grading of 2.36mm and 4.75mm sieve sizes is the second crucial element of porous asphalt pavement. The Open-Gap gradation enhances the mechanical qualities of a porous asphalt pavement by maintaining a constant degree of stone-to-stone connectivity. The function is more sustainable and self-cleaning as a result of the increased pore size and air-void connection.

Zanoni et al. (2019) investigated the numerous benefits of using porous asphalt pavement compared to other forms of pervious pavement. Its high permeability, water quality improvement, longevity, skid resistance, and heat island mitigation make it a preferred choice for sustainable stormwater management. However, it is essential to consider site-specific conditions, maintenance requirements, and cost-effectiveness when selecting the most suitable pervious pavement solution. Further research and field studies are necessary to evaluate its performance and optimize its design and construction techniques.

Lederle et al. (2020) compared in their study various techniques for calculating the infiltration rate of pervious concrete. Pervious concrete is essential for storm water management because it allows water to travel through its porous structure. For assessing the performance and efficacy of pervious concrete pavements, accurate monitoring of the infiltration rate is essential. It emphasizes the significance of precisely monitoring the rate of pervious concrete's infiltration and compares the many approaches used to do so. Further research is needed to refine and standardize the measurement methods, considering factors such as variations in pavement properties, compaction methods, and clogging effects. Developing reliable and efficient measurement techniques will contribute to the evaluation and optimization of pervious concrete pavements for effective storm water management.

Zhu et al. (2018) discussed the use of simulation results and explored the benefits of permeable road surfaces in lowering the danger of urban discharge storms. Low-impact development (LID), which can reduce peak flood flows and the urban surface runoff coefficient, includes permeable roads as one of its components. The six-lane, two-way road in Nanjing that would be the research area was selected. The storm water management model (SWMM) was used to evaluate the effects of several pavement constructions (drainage surface, porous pavement, and porous road) during various rainstorm scenarios on reducing surface runoff and controlling urban rainwater. The simulation's findings demonstrate that while a drain surface can somewhat lower surface runoff, it has little impact on hysteresis and flood peak reduction. The permeable pavement may delay peak hours and lower peak runoff and flood levels. In terms of reducing runoff's efficiency and flood peak, the permeable road has a more significant impact in order to significantly alleviate the burden on urban drainage systems and lessen the likelihood of precipitation floods.

Bonicelli et al. (2015) presented an investigative study on the effect of fine sand added to permeable concrete compacted by different methods. This study examines the benefits of using permeable concrete pavement as the best management method for stormwater management. It contains information on the compression energy and sand percentage added to this reference mixture, as well as investigated parameters such as bulk density, void ratio, dewaterability, etc. Outcomes are presented graphically and tabularly throughout the study.

Sukla and Gupta (2020) experimented with previous concrete's strength and mix design. The interconnected void content allows for high porosity. Between 0.40 and 0.50 is the water-to-cementitious material ratio. Different water-to-cement ratios were used in the designs. Different exposure circumstances are represented by these ratios. Various proportions of coarse aggregate were used. It is focused on the strength and penetration of each part of the permeable concrete mix and the influence of crushed stone as fine aggregate. Road surface design has made use of permeable concrete's mechanical qualities. The ideal ratios, which show that the concrete is permeable and has good crushing and flexural strength, have been found.

2.6 Review on Piezo Electric Energy harvesting

Cali and Renato (2013) defined piezoelectricity as the process by which some materials develop an electric charge in reaction to mechanical stress. They talked about PZT, polyvinylidene fluoride (PVDF), and ZnO, which are all piezoelectric materials that are extensively employed in energy harvesting applications. Different piezoelectric energy harvester layouts and designs were investigated. It discussed the significance of mechanical and electrical impedance equalization in order to maximize energy extraction. The authors also talked about ways to improve energy conversion efficiency, such as employing resonance and vibration amplification processes. The study discussed the difficulties and constraints of piezoelectric energy gathering, such as the trade-off between energy conversion efficiency and bandwidth, as well as the requirement for dependable packaging and environmental protection.

Priya and Inman (2009) investigated the possibility of harnessing environmental energy, such as vibrations, solar radiation, temperature gradients, and electromagnetic fields, to power electronic systems and devices. Highlighting the need for energy harvesting devices as an alternative to existing battery-powered systems, which frequently require replacement or recharging. They emphasize the growing demand for portable, self-sustaining gadgets across a variety of industries, including healthcare, transportation, and infrastructure monitoring. Examine the uses of photovoltaic technologies, which catch solar energy and turn it into usable electrical power, in exterior wireless sensor networks, remote sensing, and building energy management systems.

Minazara et al. (2008) concentrated on gathering energy from bike vibrations and using it to power portable gadgets with a piezoelectric generator. The authors conducted experiments to assess the piezoelectric generator's effectiveness in turning mechanical vibrations into electrical energy. They successfully proved the viability of utilizing bicycle vibrations to power portable gadgets. The study emphasized the potential of this energy harvesting approach for applications such as charging phones or powering GPS gadgets while cycling. The writers addressed concerns such as generator positioning, output optimization, and compatibility with various bike types. The study demonstrated the feasibility of using ambient vibrations in everyday activities to create sustainable energy for portable devices, thereby lowering dependence on traditional power sources.

Wright and Rabaey (2004) researched the creation of a piezoelectric generator as a technical enabler for self-powered wireless sensor networks. The modeling, design, and optimization of a two-layer bending element-based piezoelectric generator were described in the study. An analytical model was created and tested, which provided design insights and served as the foundation for optimization. The findings of the developed generator were published in the publication, which indicated 375 output power from the vibration source of 2.5 meters per square second at 120 Hz in the tiny size of 1 cm^3. The same vibration source was used to power the generator as well as a specially made 1.9 GHz radio transmitter. The study demonstrated the feasibility of piezoelectric vibration-based generators for self-powering wireless devices. The results aided the development of wireless sensor networks by providing a long-term and effective energy harvesting option.

Yuan et al. (2008) explored the theoretical underpinnings of ultrasonics, such as wave propagation, scattering, and imaging methods. They presented the findings of experimental research that was carried out to confirm theoretical models and investigate the capabilities and limitations of ultrasonic technology. The article also highlighted the development of ultrasonic applications in underwater acoustics. The authors explored the possible benefits and limitations of adopting ultrasonic devices in these various sectors. Overall, the report offered a complete account of ultrasonic technology improvements up to 2008. It contributed to the better knowledge and development of ultrasonics by providing useful insights into theoretical concepts, experimental procedures, and practical applications.

J.S. Harrison (2001) concentrated on piezoelectric polymer characteristics and applications. A comprehensive synopsis of the research on these materials was to be presented in this article. The author focused on the unique capabilities of piezoelectric polymers to convert mechanical stress into electrical energy and vice versa. Polyvinylidene fluoride (PVDF), polyvinyl fluoride (PVF), and copolymers were among the piezoelectric polymers studied. The research went into depth about the manufacturing procedures and strategies used to improve the piezoelectric capabilities of these polymers. The author also emphasized the difficulties in attaining consistent and dependable piezoelectric performance. Furthermore, the research investigated the uses of piezoelectric polymers in many sectors, including aerospace, automotive, and medical domains. Examples include its application in sensors, actuators, energy harvesting devices, and transducers. The paper's study proved the promise and adaptability of piezoelectric polymers in a variety of practical applications.

Hillenbrand and Sessler (2008) focused their research on the polymer electrets' piezoelectric properties. The researchers looked into cellular polypropylene (PP) and porous polytetrafluoroethylene (PTFE) polymers with thicknesses between 50 and 100 microns. Electromechanical, optical, and acoustic methods were used to study the piezoelectric d33 coefficients for both quasistatic and dynamic applications. The quasistatic coefficients for cellular

PP were found to vary from 100 to 350 pCrN, whereas they were much lower for porous PTFE. Up until around 50 kHz, the cellular PP coefficient decreased with increasing frequency. Thereafter, it started to increase towards resonance at about 300 kHz. On the other hand, bilayer or multilayer structures showed noticeably higher quasistatic coefficients, up to 20,000 pCrN for specific pressure combinations. Higher frequencies decrease coefficients in single-layer systems. This impact has a linear connection with load pressure, especially at low pressures. Air-gap systems had pressures of up to 100 Pa, whereas cellular PP systems had pressures of a few kPa. In general, the study provided details on the quasistatic and dynamic piezoelectric coefficients of systems made of polymer foams and films.

Klimiec et al. (2008) investigated the use of piezoelectric polymer sheets to transfer mechanical energy into electrical energy. The researchers emphasized the potential of these materials for powering electronic gadgets, notably wearable computing. Piezoelectric polymers can now be used as power converters for human-powered devices thanks to improvements in electronic technology, such as the widely used submicron low-power CMOS techniques. It eliminates the requirement for traditional battery power sources, which has been a key obstacle to wearable gadget adoption. The study focused on the use of a copolymer known as polyethylene-polypropylene (PE-PP) as a power generator in shoe insoles. The researchers assessed the maximum power that could be created from walking energy using an 11-mm-thick PE-PP foil. A single, one-second stride yielded 340 nJ of electric energy, or a frequency equal to 1 hertz (Hz).

Badel and Abdelmjid Benayad (2006) summarized their work on vibration-powered electrical generators based on single crystals and nonlinear processes. They concentrated their research on developing extremely efficient electrical generators that could extract energy from vibrations. They investigated the use of single crystals, which have special qualities that lend themselves to energy conversion. They also looked at nonlinear processes that may improve the performance of the generators. Using single crystals and nonlinear processes, the researchers successfully created vibration-powered electrical generators. These generators performed admirably in terms of translating mechanical vibrations into electrical energy. The study described the specifics of the design, materials employed, and experimental findings. Overall, the research sheds light on the use of single crystals and nonlinear processes in the production of extremely efficient vibration-powered electrical generators.

Karami and Bilgen (2011) investigated energy harvesting employing beam-like unimorph structures and single-crystal piezoelectric materials in an experimental and theoretical investigation. Three types of piezoelectric materials were evaluated in the study. These materials had been used in the construction of unimorph cantilevered beams. Researchers conducted trials in which the gadgets were exposed to harmonic base acceleration to corroborate their findings. The experimental data were utilized to validate the energy harvester's accurate electromechanical model. In terms of power generation, single-crystal harvesters beat polycrystalline devices in the study, which tested the performance of numerous substrate materials, including stainless steel. To understand these discrepancies, the study examined the mechanical transmissibility and coupling figures of merit of the harvesters. The optimal substrate thicknesses for various materials were determined.

Li et al. (2014) looked into the current level of knowledge of piezoelectric energy harvesting technology, which is primarily used for low-frequency applications between 0 and 100 Hz. The aim was to investigate new means of powering electronic devices by collecting energy from mechanical vibrations or impacts, therefore reducing the need for battery changes. The typically utilized piezoelectric materials' relatively high elastic moduli, however, posed a difficulty for researchers in optimizing the energy output of piezoelectric energy harvesters for low-frequency applications. An overview of the evolution of piezoelectric energy harvesting technology for low-frequency applications was provided by the study. It addressed the difficulties caused by the large elastic moduli of piezoelectric materials and suggested numerous ways for increasing the power output of these energy harvesters.

Poria et al. (2012) studied the vibration energy harvesting of a MEMS (micro electro mechanical systems) device using an epitaxial piezoelectric thin film. The study's goal was to look into the possibility of collecting energy from mechanical vibrations using a MEMS device. The research focused on the use of an epitaxial piezoelectric thin film, which improves piezoelectric characteristics. The researchers wanted to create a mathematical model and simulation to better understand the energy harvester's behavior and performance. They created a mathematical model that took into account the epitaxial piezoelectric thin film's features, such as its piezoelectric coefficients and dimensions. The researchers used simulation to examine the efficacy of the vibration energy harvester and its potential for practical applications. They investigated several aspects, such as input vibration frequency and amplitude and the effect of the physical dimensions of a piezoelectric thin film.

Johnson et al. (2006) investigated a 31-unimorph piezoelectric cantilever beam for converting mechanical vibration into electrical energy for low-power electronic devices. The study's goal was to provide a design technique that optimized the cantilever beam for a given application. The process entailed examining vibration data from a machine, including frequency and amplitude. This information was included in the beam's final design, with an emphasis on determining the frequency range where the energy-collecting device would create the most energy. The researchers presented a broader approach to constructing energy harvesters for a variety of applications. They emphasized how the thickness and kind of materials for each layer of the cantilever beam were chosen independently of the vibration data. This guaranteed that the optimization process was not hampered.

Mineto et al. (2010) studied the creation of a piezoelectric cantilever beam for power harvesting. They investigated the beam's behavior and performance using modeling and simulation. The study sought to comprehend the operation of the piezoelectric cantilever beam and its potential for power generation. The researchers used simulation tools to create a model and study the properties of the beam. They investigated the piezoelectric characteristics of the beam and its response to various stresses and displacements throughout the study. They also used the simulated model to assess the efficiency of electricity generation. Overall, the research gave useful insights into the modeling of a piezoelectric cantilever beam for power generation. Their research focused on understanding the beam's behavior and potential for generating electricity, with simulation approaches utilized to aid in the investigation.

Lina and Denughua (2011) examined the cymbal transducer, a new advancement in metal-ceramic piezocomposite transducers distinguished by a greater effective piezoelectric coefficient (de33) than typical piezoelectric ceramics. The study's goal was to explore the cymbal transducer's operating mechanism and create a finite element analysis (FEA) model with ANSYS software. Brass foil served as the end cap electrode, and PZT-5A piezoelectric ceramic served as the piezoelectric phase for the cymbal transducer. They investigated the link between the cymbal's longitudinal displacement and the force applied to the brass foil. They also estimated the effective piezoelectric coefficient (de33) and compared the findings to experimental data. Using ANSYS, they offered insights into the effective piezoelectric coefficients of the cymbal transducer. Their effort included investigating the behavior of the transducer, developing a FEA model, and verifying the results by comparing them to experimental data.

Kim et al. (2004) tested the practicality of obtaining electrical energy in a dynamic environment from mechanical vibrations using a piezoelectric "cymbal" transducer. The mechanical vibrations were focused at frequencies ranging from 50 to 150 Hz, with force amplitudes of around 1 kN, replicating vibrations usually observed in automotive engines. The researchers determined that the "cymbal" transducer's metal-ceramic composite construction held considerable promise at such intense stress settings. The metal cap component contributed to the ceramic material's longevity, allowing it to tolerate high loads and stress amplification. To evaluate the transducer's performance, early experiments were carried out with a 29 mm diameter and 1 mm thick cymbal transducer at a frequency of 100 Hz and a force of 7.8 N. At the set frequency and stress level, the cymbal transducer generated 39 mW of power when tested across a 400 kilo ohm resistor. The researchers created a DC-DC converter capable of transferring thirty mW of power to a lower impedance load of 5 kilo ohms to promote efficient energy transfer. The converter had a duty cycle of 2% and a switching frequency of 1 kHz.

Kim et al. (2005) concentrated on vibrations with frequencies ranging from 100 to 200 Hz and forces ranging from 100 to 200 N. The introduction of a thicker steel cap in the transducer construction improved the ceramic material's durability, allowing it to handle larger alternating current (AC) loads and stress amplification. Performance of the cymbal transducer was evaluated using a pre-stress load of 67 N at 100 Hz and a 70 N AC force. When measured across a 400-kiloohm resistor at this pitch and intensity, the transducer produced 52 mW of power. To maximize performance, different thicknesses of the ceramic were tested with a diameter of 29 mm. According to the outcomes, a 1 mm-thick PZT ceramic paired with a 0.4 mm end cap produced the maximum power output. The researchers adjusted the transducer and cap materials to withstand the high dynamic pressure. They discovered that employing a higher piezoelectric voltage-constant ceramic material produced more power.

Bejarano et al. (2008) created a cymbal transducer prototype that was especially optimized for power ultrasonic applications. A piezoceramic disc was placed between two metal end caps to form the transducer. The design aims to improve the mechanical connection between the piezoceramic material and the surrounding medium, thereby enhancing energy transfer efficiency. Experiments were carried out to assess the performance of the cymbal transducer prototype. The power handling capabilities, frequency responsiveness, and efficiency were all evaluated by the researchers. Furthermore, the researchers studied the influence of various design factors on transducer performance, such as end cap thickness and piezoceramic material characteristics. They were able to optimize the transducer's power output and efficiency by systematically varying these settings. The optimization of design parameters resulted in increased power output and efficiency. These discoveries advance power ultrasound systems and give vital insights for the creation of efficient transducers in this sector.

Chen et al. (2011) investigated the performance and possible uses of an energy-harvesting PZT diaphragm. Experiments were carried out to assess the harvester's performance under various settings. The researchers discovered that boosting the harvester's pre-stress resulted in increased energy output while reducing the resonance frequency. This study revealed that pre-stress was important for harvester performance. The researchers also identified a contacting component between the proof mass and piezoelectric disc as a crucial factor impacting harvester performance. This underlined the need to optimize the interplay of these components in order to improve energy harvesting efficiency.

2.7 Summary of the literature

Various studies on porous concrete, permeable asphalt, managing stormwater, and piezoelectric energy harvesting have been reviewed in this literature review. The research on permeable concrete focused on a variety of topics, including the development of test specimens, crushing and splitting capabilities, hydrological and mechanical features, and the use of additives to improve strength and durability. The porous asphalt study looked at its composition, filtration capabilities, mechanical performance, and noise reduction possibilities. Furthermore, the application of GGBS as a substitute for cement in concrete was researched in order to improve its characteristics and sustainability.

The research underlined the usefulness of permeable pavements in lowering surface runoff, enhancing the quality of water, and mitigating flood hazards in the context of managing stormwater as well as sustainable urban development. According to the studies, permeable pavements have a favorable influence on limiting urban precipitation and managing stormwater, making them attractive options for environmental sustainability.

Furthermore, the study on the harvesting of piezoelectric energy revealed new materials and design concepts for capturing energy from environmental vibrations. The investigations demonstrated the promise of piezoelectric technology for powering electronic devices and wireless sensor networks, as well as its potential uses in underwater acoustics and low-frequency energy harvesting.

Overall, these investigations add to our understanding of the characteristics, performance, and possible applications of porous concrete and porous asphalt, along with piezoelectric energy harvesting. The examination of the literature shows the importance of these resources and innovations in building, managing stormwater, environmentally friendly practices, and energy-efficient systems. However, it also identifies deficiencies in research and the need for more study in optimizing parameters for design, investigating the interplay of numerous elements, and analyzing long-term behavior for improved performance as well as real-world use in the relevant domains. These research' findings help to further our understanding and execution of these environmentally conscious and innovative solutions to building and environmental concerns.

2.8 Research gap:

The following are the research gaps found from the corpus of studies on porous concrete, porous asphalt, managing storm water, GGBS-based concrete, and piezoelectric energy harvesting:

1. The use of porous pavement is not very popular in road construction because of its weak performance. More research is needed to improve the performance and properties of porous concrete by using alternative materials.
2. The inclusion of LDPE and crumb rubber in porous asphalt mix and its reaction on properties and performance should be thoroughly examined.
3. More study is needed to comprehend the influence of alternative material like steel slag as replacement of coarse aggregate in porous concrete under various loads and environmental circumstances.
4. Prior research has shown the influence of GGBS in rigid pavement. So a detail laboratory study is required to inspect the effect of GGBS based porous concrete on structural and hydrological properties.
5. Many studies were done in specific areas or in unique settings, limiting their generalizability. More research needs to be conducted to determine the findings' relevance to diverse geographic regions and climates. Also study is needed to assess the noise reduction capacity of porous concrete.
6. In order to evaluate the total affordability of porous concrete compared to conventional concrete in various building scenarios, detailed economic assessments are required.
7. More research into novel and creative piezoelectric materials that might offer increased efficiency as well as performance in energy harvesting applications is required.
8. There are research gaps in investigating the feasibility and usefulness of the harvesting of piezoelectric energy at frequencies that extend beyond the low-frequency spectrum.
9. Substantial field investigations and applications in the real world are necessary to evaluate the performance and resilience of piezoelectric energy harvesting devices under real-world operating circumstances.
10. The absence of defined design guidelines and methods for harvesting piezoelectric energy makes comparing and replicating results from various research efforts difficult. Design

recommendations might increase the efficiency and dependability of harvesting energy from piezoelectric devices.

Addressing these research deficiencies would greatly contribute to the progress and practical application of these technologies, ensuring their efficacy, sustainability, and viability in a variety of applications and sectors.

CHAPTER- 3

MATERIALS AND METHODOLOGY

3.1 Materials required for Porous Pavement Studies:

3.1.1 General:

This chapter gives a brief description of the materials needed for various experimental experiments on porous pavements. Seven distinct research studies concentrating on various features of porous pavement, such as the utilisation of crumb rubber, GGBS, LDPE, and steel slag, have been explored. Each project includes particular materials that are critical to the performance and features of the permeable pavements under consideration.

3.1.2 Aggregate:

Aggregate is a key ingredient utilized in all studies to offer rigidity and strength to porous pavements. Depending on the unique aims of each study endeavor, multiple kinds of aggregates are used. Stone aggregates are used in porous asphalt pavement projects and are obtained from regional suppliers or firms. The aggregate grading meets the requirements of organizations such as NAPA and IRC 111-2009. Coarse steel slag aggregates (CSSA) as well as natural stone aggregates (NSA) are employed in varied amounts in the project focused on the utilization of steel slag as a partial substitute for stone aggregate.

Figure. 3.1 Aggregates

Figure. 3.2 Bitumen

3.1.3 Bitumen:

In the permeable asphalt pavement research, bitumen is employed as a binding agent in bituminous concrete mixes. Because it is acceptable for Indian pavements, VG-30 grade bitumen is typically used in these projects. The fundamental property tests, which include penetration, specific gravity, and viscosity, have been carried out to guarantee that the bitumen is compatible with the aggregate and other components.

3.1.4 Chemical Additives:

Several studies have found that chemical additives play an important role in improving the qualities of porous pavements. In one project, for example, crumb rubber is used to improve the qualities of open-graded bituminous mixtures. In another investigation, LDPE (plastic carry bags, packages, and PET bottles) is employed as a coating of plastic material for aggregates, which aids in noise reduction and energy generation via piezoelectric energy harvesting.

3.1.5 Ground Granulated Blast Furnace Slag (GGBS):

Ground granulated blast furnace slag, or GGBS, is a fine powder produced by quenching the molten iron slag (a byproduct of iron and steel production) from a blast furnace that has been quenched in water or steam. GGBS, or ground granulated blast furnace slag, is a byproduct of iron production that, when added to concrete, enhances its qualities such as workability, strength, and durability. The substance is created by heating iron ore, limestone, and coke at around 1500° C. The procedure is carried out in the blast furnace. The creation of GGBS is indirect. Molten iron and molten slag are byproducts of iron production. The molten slag is made up of silica, alumina, and certain oxides. After cooling, the slag is granulated. It is permitted to flow via high-pressure water for this purpose. This causes the particles to quench, resulting in granules with diameters smaller than 5mm. Cao, SiO_2, Al_2O_3, and MgO are the primary elements of blast furnace slag. The aforementioned are the minerals present in the majority of cementitious materials. The particles are then dried and processed into a fine powder in a spinning ball mill, resulting in ground, granulated slag from blast furnaces. Different ways can now be used to carry out the main process known as quenching.

Figure 3.3 Ground Granulated Blast Furnace Slag (GGBS)

3.1.6 Cement:

Cement is a binding substance that is used to join many types of construction materials. Lime was employed as a cementing element prior to the development of regular Portland cement. Currently, the majority of cement concrete used in the construction of buildings is made from Ordinary Portland Cement. It evolved from other varieties of hydraulic lime that were used in England during the mid-nineteenth century and is typically derived from limestone. It is a finely ground substance that is formed by igniting materials to generate clinker. The additional components are added in modest amounts after the cement has been ground. All of the standard standards should be met by the cement.

Figure 3.4 Cement

3.1.7 Fine Aggregate:

Fine aggregates are used in the creation of some permeable concrete mix designs. Local sand is typically utilised as a filler ingredient in the mix to boost strength and fill gaps. The quantity of coarse aggregate is used to calculate the fine aggregate percentage.

Figure 3.5 Fine aggregate

3.1.8 Water:

A vital component in the creation of porous concrete mixes is water. To assure the integrity and performance of the concrete, fresh and contaminant-free water has been utilised. Water is also utilised in certain experiments to cure the concrete once it has been prepared.

3.1.9 Superplasticizer:

Superplasticizers are the additives that are used to prepare higher-strength concrete. This is also called as water reducers of high range. These are the chemical ingredients that allow concrete to be made with 30% less water. The superplasticizer (AURAMIX 200) employed in this investigation is based on polycarboxylate ether. Depending on the weight of the cement, it is mixed with water at a rate between 0.7% and 0.8%.

Figure 3.6 Superplasticizer

3.1.10 Energy harvesting by pedestrian movement on the Piezo Crystal embedded footpaths:

Two brothers named Pierre and Jacques discovered the piezoelectric effect in 1880, which refers to a specific crystal's ability to produce electricity when put under mechanical stress. These substances are known as piezoelectric substances. The process for energy harvesting with piezo crystals is explained in this section. Walking on the streets releases energy that is not immediately put to use. Meanwhile, using fossil fuels to generate power depletes supplies and pollutes the environment. Researchers are therefore interested in the production of power using renewable energy sources. In the current work, the creation of voltage from piezoelectric material using the pressure exerted by walkers is also being studied. The proposed power generation model is illustrated in Figure 3.7.

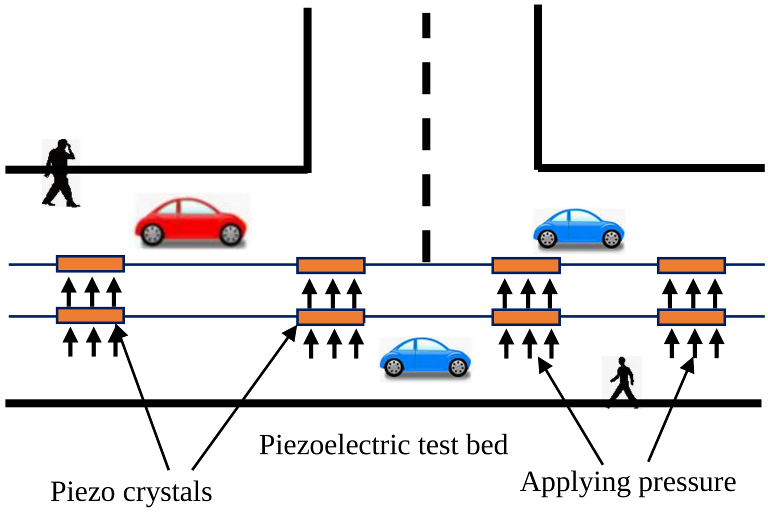


Figure 3.7 Proposed model of power generation

Roadside walkways are used by pedestrians to fulfill daily needs like getting to work, shopping, etc. It is a great way to collect sustainable pedestrian energy and improve the road system. In this instance, eight piezo crystal plates are linked together via parallel and series connections. In this instance, two parallel sets are created to boost current, while four plates are joined in series to enhance voltage. The experimental setup is shown in Figure 3.8.

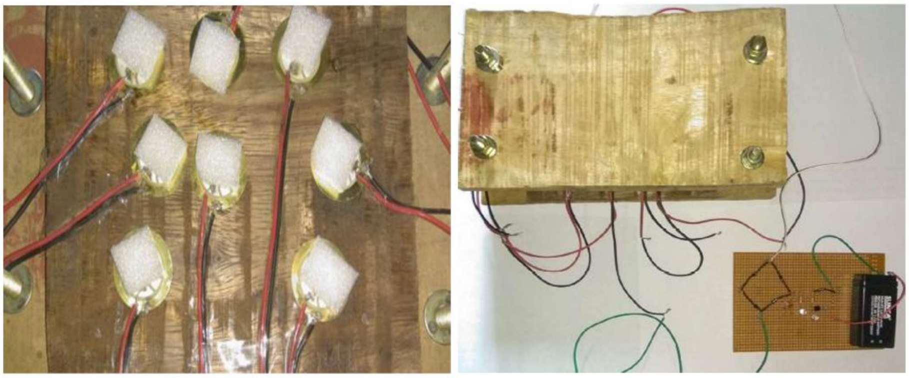


Figure 3.8 Experimental Setup for Pedestrian Energy Harvesting

3.1.11 Crumb Rubber:

Crumb Rubber is rubber in the form of powder made from scrap and worn-out tires. Old, used, and scrap tires are available in huge quantities in every country, and almost all of them have no use. Since there is no such alternative use of scrap and used tires, in this investigation, open-graded bituminous mixes characteristics are enhanced by the use of shredded Crumb Rubber Powder.

Figure 3.9 Crumb Rubber

3.1.11 Summary:

This chapter provides a detailed list of items needed to undertake various experimental research projects on porous pavements. Each project comprises a distinct blend of components, additives, and aggregates targeted at attaining specific goals such as improved strength, resilience, and permeability, as well as energy harvesting capabilities. Proper material selection and testing are critical when assessing the success and efficiency of the permeable pavement systems under consideration.

3.2 Methodology:

3.2.1 General:

The technique used in this thesis on permeable pavement includes seven unique studies, each addressing various research objectives relating to the design, composition, features, and uses of porous pavement. The projects have been meticulously planned to give a thorough knowledge of porous pavement and to investigate its possibilities in a variety of areas, including strength increase, permeability enhancement, engineering feature analysis, noise reduction, and energy harvesting. The sections that follow detail the study strategy, preparation of samples, and testing processes that were used in each project.

3.2.2 For using Crumb Rubber:

3.2.2.1 Sample Preparation:

The Marshall Mix Design technique is used for porous asphalt pavement mix design. Heat local aggregates with specified grades to 180°C and mix with varied quantities of shredded crumb rubber

(0.5%, 1%, and 1.5% by weight of aggregate). The binder is then heated to 160°C before being applied to the samples.

3.2.2.2 Marshall Method of Mix Design:

The Marshall technique is used to assess the bituminous mix's stability and flow values. In this investigation, crumb rubber-modified concrete is combined with open-graded bituminous concrete. For medium-volume roads, samples are prepared using the Marshall method.

3.2.2.3 Permeability Test:

Permeability is a property of porous asphalt pavement that allows water to percolate through the pores present in the pavement structure. In this study, Marshall Sample's permeability is calculated by the falling head permeability method. The set-up consists of a Marshall sample, a circular collar, a volume measuring funnel, a thin plastic sheet of 100 microns, a seal tap, mesh, and wax. At first, the plastic sheet is wrapped around the Marshall sample for up to 1/3 of its length and taped carefully. Additionally, wax is wrapped around the edges of the sample. With a volume measurement funnel, water was poured while the sample was wrapped and placed over a circular collier with a mesh.

3.2.3 For using Ground Granulated Blast Furnace Slag (GGBS):

3.2.3.1 Mix Proportioning:

It entails mixing pervious concrete according to ACI 522R-10 along with IS 10262:2019 requirements using the absolute volume concept. Various water-cement ratios and GGBS percentages as a partial substitute for cement are investigated. To achieve strength and permeability requirements, a 5% fine aggregate composition is used.

3.2.3.2 Sample Preparation:

A pan mixer is used to assure adequate mixing of the cement, GGBS, the fine aggregate, along with coarse aggregate in pervious concrete samples. The mixtures are crushed with a tamping rod before curing underwater for 7 to 28 days.

3.2.3.3 Tests on Concrete:

Various tests are performed to evaluate the engineering qualities of pervious concrete, comprising compressive strength, split tensile strength, flexural strength, and permeability, along with porosity testing.

- **Compressive Strength**

  Concrete has an important property like compressive strength. All of the other characteristics of concrete are inversely correlated with compressive strength. With the help of this test, it is possible to tell whether concrete pouring has been done correctly or not. A cubical mold of size 15 cm by 15 cm by 15 cm has been utilized. The cubes have been examined using compression testing equipment after curing for 7 days and 28 days, respectively.

- **Split tensile strength:**

  When designing structural lightweight concrete components, split tensile strength is applied to determine the development length of the reinforcement and analyze the concrete's shear resistance. Using this test method, a diametrical force is applied down the length of a concrete cylinder until failure occurs within the predetermined limit. The specimen's maximum allowable force is multiplied by the appropriate geometrical parameters to determine the split tensile strength. The height and diameter of the cylindrical mold are 200 mm and 100 mm, respectively.

- **Flexural strength:**

  The resistance of a concrete beam to breaking when bent is known as flexural strength. For testing, 50-cm-long concrete beams are loaded to assess their strength. This test is carried out using an experiment with four loading points. Forces are applied to the four different points during the four-point loading test. The beam is supported at two points below, 5 cm from the ends. The usual measurements are 15 × 15 × 70 cm. Instead, specimens 10 × 10 × 50 cm may be used, provided the aggregate nominal size does not exceed 19 mm.

- **Permeability:**

  In this study, the falling head permeability test apparatus was used to evaluate the permeability property of porous concrete specimens. The permeability test set-up is the consistency of a graduated cylindrical tube to measure the hydraulic heads and valves to control water flow. The setup has a steel mold to retain the specimen and an above-ground tank for continuous water delivery. The duct tape has been used to steal the concrete specimen in order to stop any lateral water movement. A commercially available water-proof sealant substance has been used to cover the joint where the specimen and the cylinder meet. By alternately controlling the valves, the specimen has been given time to thoroughly soak in water prior to the test. This is done to make sure the specimen doesn't contain any air voids.

- **Porosity:**

The ASTM D 1754 water displacement technique has been used to assess the porosity by using specimens of cylindrical shape with a diameter of 100 mm and a height of 200 mm. By calculating the difference between the dry and submerged weights, the porosity has been estimated. After the proper curing of all the samples, their submerged heights have been recorded. Then the samples were kept dry in the thermostatically controlled oven at 110° C for 24 hours. The formula listed below is used to calculate the porosity property.

3.2.3 For using Low Dense Polyethylene (LDPE):

3.2.3.1 Marshall Mix Design of Bituminous Concrete:

It entails applying the Marshall technique to build a bituminous concrete mix. To make a coating, shredded plastic (LDPE) screened through a particular mesh size is combined with heated aggregate. To establish the optimal binder content, samples with varied plastic contents are created.

3.2.3.2 Permeability Test:

The constant head permeability technique is used to determine the permeability of the Marshall samples. This test evaluates the porous bituminous pavement's capacity to promote water circulation.

3.2.3.3 Indirect Tensile Strength Test:

The static method is used to measure the indirect tensile strength (ITS) of bitumen mixtures, which aids in determining how resistant a certain mix is to moisture susceptibility. At their OBC, mixes with varying crumb rubber and nano silica contents underwent static indirect tensile tests.

3.2.5 For using Steel Slag:

3.2.5.1 Marshall Mix method:

To establish the optimal binder concentration for porous asphalt mixes containing or excluding steel slag as a substitute in part for stone aggregate using ASTM D6927.

3.2.5.2 Permeability Test:

The constant head permeability method is adopted to determine the marshal sample's permeability. A tripod stand, a marshal collar, a water collecting container, and a volume measurement device make up the setup for this technique. Marshall Water flows into the sample with mould from a water tap at a constant height from the side with the most mould inserted into it. The sample is fastened to the collar. The volume of water is then estimated as the sample percolates over a period of time. With the aid of IS: 3085-1965, the permeability coefficient is determined from Darcy Law.

3.2.5.3 Cantabro Abrasion Test:

The Cantabro abrasion test method is adopted to determine whether the compressed porous asphalt course (PAC) specimen has a sufficient level of durability. Most agencies today recommend applying this test to PACs with a mixed design, either as a requirement or as an option. To evaluate the mixture's unaged abrasion loss, a compacted sample of the PAC mix was placed in a Los Angeles abrasion drum with no abrasive charges. At a speed of 30 to 33 rpm, the machine was then spun for 300 revolutions. The ideal working temperature is 25.5°C. The specimen's starting weight is measured first (A), and then its ultimate weight (B) is determined after 300 rotations. When comparing the weight of fragmented particles, one can measure abrasion loss compared to the original weight of the specimen.

3.2.6 For the effect of Coarse Aggregate (CA):

3.2.6.1 Mix Proportioning:

It entails mixing proportions based on the standards of ACI 522R-10 along with IS 10262:2019, with a continuous void of 15%. The study used a total of three kinds of coarse aggregates that varied in form and size. For each category, samples are generated at various water-cement ratios.

3.2.6.2 Tests on Concrete:

On produced permeable concrete samples with various coarse aggregate dimensions and shapes, flexural strength, compressive strength, permeability, along with porosity tests are performed.

3.2.7 For Vehicular Noise reduction:

3.2.7.1 Location of the study:

This research focuses on the usage of permeable asphalt material for minimising noise in road construction. Pedestrian surveys are carried out at several areas across Agartala to monitor and document pedestrian flow.

3.2.7.2 Noise Level Study:

Sound level metres are set at strategic points along roadways with porous asphalt as well as regular asphalt pavements to evaluate and contrast noise levels throughout the day and at night.

3.2.8 For Piezoelectric Energy Harvesting:

3.2.8.1 Modelling of Piezo Electric Harvester: The piezoelectric kinetic energy harvester is a second-order mass-spring-damper device that converts mechanical energy via pedestrian movement into electrical energy.

3.2.8.2 Sensitivity Analysis:

Statistical analysis is used to determine the degree of sensitivity of voltage production to parameters such as pedestrian pressure and walking pace.

3.2.9 Summary:

The study strategy, sample preparation techniques, and testing protocols used throughout each of the seven studies conducted for the current dissertation regarding porous pavement were explained in this chapter. The study design guarantees a thorough examination of many elements of porous pavement while offering useful insights into its possible uses in road building and sustainability. The next chapters will give the data and analysis from each study, together expanding one's knowledge of porous pavement.

3.3 Tests on Aggregate:

- **Specific Gravity & Water Absorption (conforming to IS 2386: Part III-1963)**

  By dividing a solid's mass by the mass of an equivalent volume of pure water at a specified temperature, its specific gravity can be calculated. The strength or material quality of stone aggregate is gauged by its specific gravity. Since aggregates have permeable voids, apparent specific gravity and bulk specific gravity are used as measurements of the specific gravity of aggregates. Apparent and bulk-specific gravities and their differences depend on how many water-permeable gaps are present in the aggregates. The hardness of a rock can be determined by how much water it can absorb. High water absorption makes the stone more porous by nature, making it generally inappropriate unless it is determined that it is suitable depending on strength, impact, and hardness.

Figure 3.10 Pycnometer method

- **Shape test (conforming to IS 2386: Part l)**

  The amount of flakiness and elongated particles in an aggregate can be used to determine its form. The weighted percentage of aggregate particles is the definition of the flakiness index, whose smallest dimension is less than three-fifths of their mean size. Following the flakiness index test, the flaky particles are removed from the aggregate mass, and the non-flaky particles are used in the elongation test. The proportion of aggregate particles by weight whose smallest dimension is smaller than 1.8 times their mean size is known as the elongation index.

Figure 3.11 Elongation and Thickness gauge

- **Abrasion test (conforming to 1S 2386: Part IV-1963)**

Aggregate hardness is assessed using an abrasion test. The best method for measuring the hardness attribute is the Los Angeles abrasion test, which India has adopted as a standard. The main goal of this test is to gauge how much wear happens when steel balls employed as an abrasive charge come into contact with the aggregate's particles. Depending on the grade of the sample, a cast iron abrasive charge with a 48-millimeter diameter and a weight of 340–445 g is added to the aggregates. A 5–10 kg sample of aggregate is required for this, and after between 500 and 1000 drum revolutions, the aggregates are passed through a 1.7 mm sieve; the percentage of the aggregates that pass through the sieve is then represented as a percentage of wear by the weight of the entire sample.

Figure 3.12 Los Angles Abrasion Testing Machine

- **Crushing Strength Test (conforming to 1S 2386: Part IV-1963)**

This is one of the crucial technical requirements for a road stone. The aggregates' ability to withstand crushing brought on by moving vehicles, which is a stress brought on by moving vehicles, is measured by the test. Additionally, the aggregates must be sturdy enough to resist crushing beneath construction rollers and beneath vehicles' tough tire rims hauled by heavily loaded animals. The crushing values for aggregate give a comparative indication of the aggregate's resistance to crushing under a compressive load that is gradually applied. Low crushing values for aggregate are preferred in order to produce pavement aggregate of the highest quality. According to IS and IRC, aggregates used in concrete other than for wearing surfaces should not have an aggregate crushing value greater than 45%, and coarse aggregates used in cement concrete pavement shouldn't have one greater than 30%.

Figure 3.13 Aggregate crushing strength testing machine

- **Impact value test (conforming to IS 2386: Part IV-1936):**

The road aggregates are exposed to impact or pounding action during the construction process of pavement layers, notably compressed by large rollers and also owing to the movements of heavy commercial vehicles, and there is a risk that some stones will break into smaller fragments. Therefore, the stone aggregate needs to be sufficiently resistant to withstand fracture under quick impact loads. To ascertain the impact resistance or toughness of aggregates, an impact test is therefore conducted. The device for testing aggregate impact is made up of a metal base and a cup with a 50 mm depth and 102 mm interior diameter, a cylindrical, 13.5–14 kilogram metal hammer that falls naturally from a height of 380 mm. Three layers of aggregate, which have been hammered 25 times with a tamping rod after going through a 12.5-millimeter screen while remaining on a 10-millimeter sieve, are placed within the cylinder. Aggregate impact resistance is determined by dividing the proportion of crushed aggregate that passes the 2.36 mm screen by the sample's overall weight.

Figure 3.14 Impact Testing Machine.

3.4 Statistical Analysis:

The SPSS software has been used to do the statistical calculations. To determine the relevance of any element in altering the parameters of asphalt mixes, statistical analysis is conducted. To do this, the statistical significance of the studies was determined using the ANOVA (analysis of variance) model built into the SPSS program. The P-value is a significant finding from the ANOVA investigation. The probability error enables us to determine if a specific element has a significant impact on the measured attribute or not. For statistical computations with a higher significance level, a lower P-value is needed to demonstrate a significant effect, and vice versa. ANOVA computations are often carried out at 99% and 95% significant levels (SLs). In other words, the P values that were determined had to be less than 0.05 and 0.01, respectively.

3.5 Concluding Remarks:

This chapter briefly describes the different methods used in the present study. The testing procedures for unmodified, modified with different polymeric materials like LDPE and crumb rubber, and use of different alternative materials like GGBS and steel slag have been discussed. The variation and effect of the size and shape of coarse aggregates have been discussed. The energy harvesting from piezo crystal-enhanced footpaths by pedestrian movement has also been discussed in this section.

CHAPTER- 4

CHARACTERIZATION OF POROUS BITUMINOUS CONCRETE USING LDPE COATED COARSE AGGREGATE

4.1 GENERAL

This chapter is intended to explore the characteristics of porous bituminous concrete, which is sometimes abbreviated as OGAC (Open Graded Asphalt Concrete). The term "open graded friction course" (OGFC) is also used to describe this type of surface. Rainwater may now percolate through the pavement structure thanks to this technique. In India, there are primarily two forms of road construction: rigid pavement and flexible pavement. Bitumen roads are stiff pavements, whereas concrete roads are flexible pavements. India has a larger network of bituminous roads due to financial restrictions. However, bitumen roads have the drawback of requiring frequent upkeep. Disintegration of pavement surfaces brought on by rainwater buildup is a significant problem in the majority of India. Numerous potholes are produced when the pavement disintegrates. Finding a solution to the rising issue of holes and pavement degradation due to precipitation is just one of the primary reasons the concept of permeable bituminous pavement is heavily studied in the field of road building. This road technique reduces the likelihood of pavement degradation and potholes by not allowing rainwater to collect on the road surface.

In addition, there is a severe water table issue in many Indian towns. By 2020, groundwater would run out in 21 Indian cities, such as Hyderabad, Bangalore, Chennai, and New Delhi. According to research by the National Institution for Transforming India (NITI) Aayog. In total, nearly 100 million individuals will be impacted. Porous bituminous pavement is one potential solution to this complicated problem of water table depletion. By enabling rainfall to travel through its many layers and into the subgrade soil, porous bituminous pavement refills the groundwater table.

Low-density polyethylene (LDPE)-coated aggregates were used in this investigation to substitute the traditional open-graded bituminous mix in the anti-stripping agent. This study is being conducted in an area with moderate traffic. Plastic is a substance that cannot be biodegraded. In landfills, plastic products often take up to 1,000 years to disintegrate. The consumption of plastic has significantly expanded along with population growth. But nowadays, it is quite difficult to properly dispose of discarded plastic. Inappropriate plastic waste disposal results in the greenhouse effect, global warming, decreased soil fertility, drainage system obstructions, and other negative effects. Using it to build pavement is one of the most efficient ways to dispose of leftover plastic. When heated with aggregates, plastics cover the aggregates with a protective layer. When these aggregates are combined with bitumen, the resulting mixture demonstrates greater strength, resistance, and long-term performance. The use of plastic on roadways has made a different method of recycling post-consumer plastics possible. In India's hot and muggy atmosphere, plastic pavements are a huge benefit.

4.2 GUIDELINES FOR THE CONCEPT AND DESIGN OF POROUS BITUMINOUS PAVEMENT

The construction of asphalt pavement with pores differs significantly from that of traditional thick-graded bituminous pavement in several aspects. Different aggregate grades are employed at different levels of the porous bituminous pavement system. More coarse aggregates than fine aggregates are utilized in the construction of this type of pavement. As a result, porous bituminous pavement has a higher relative amount of air space in various layers. Following are design standards for several layers of bituminous pavement with pores:

Permeable bituminous Top Course: This coating is maintained between 50 and 100 mm thick. Between 16 and 22% of the air gaps are retained after compaction thanks to the use of aggregate gradation.

Choking Course: In this layer, aggregates with sizes ranging from 16 to 12.5 mm IS sieve are employed. This layer is preserved to a thickness of 25 to 50 mm. A 20–30% air void should be present in this stratum.

Reservoir Course: The goal of the stone reservoir course is to temporarily store rainfall, which then gently percolates into the natural subgrade below. This layer's thickness is restricted to 200 to 300 mm. In order to hold rainwater, this layer has to have 30–35% of voids. Non-woven pervious geotextile sheet is used as a layer in the construction of a foundation to prevent water penetration. Additionally, it is utilized to keep soil particles from escaping entering the reservoir stream from the subgrade by separating the subgrade from the reservoir course.

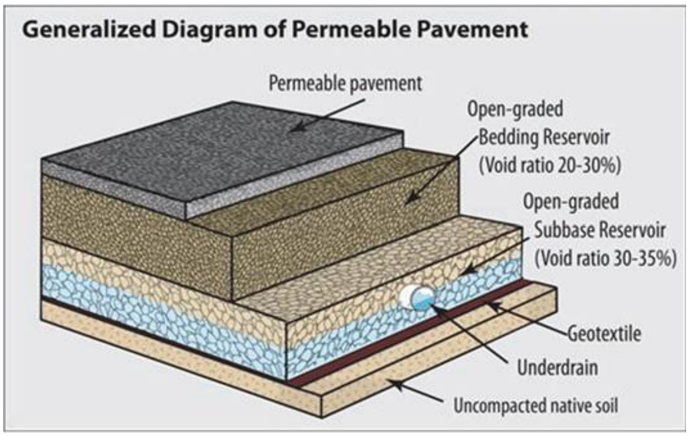


Figure 4.1 Generalized illustration of porous asphalt pavement (pinterest.com.au)

The natural soil layer is represented by the uncompacted subgrade. To keep this layer permeable, it is kept in an uncompacted state. The subgrade's slope is limited at around 5%. The infiltration rate is restricted to a range of 2.5 and 76 mm/hr. Clay soils in the inferior are undesirable. (Fig. 4.1).

4.3 MATERIALS AND METHODOLOGY

Aggregate

Stone aggregates that may be found nearby are utilized in this project. The physical characteristics of aggregates with and without plastic coating are determined. The aggregate is graded in accordance with IRC 111-2009.

Bitumen

The bitumen used to prepare the samples is standard VG-30. Basic laboratory tests are performed, including those for viscosity, specific gravity, and penetration.

Chemical Additives

Only LDPE-based products, such as carry bags, packs, PET bottles, etc., have been the focus of our investigation. Shredded plastics were retained on a 600 IS sieve after passing through a 2.36 mm IS sieve.

Super-Bond A-99 is the nanomaterial that serves as an anti-stripping agent. This additive's dose ranges from 0.1% to 0.5% of the binder content. Specifications of this, according to the producer are shown in Table 4.2.

4.4 Bituminous Concrete Using the Marshall Mix Design

Bitumen, filler, and aggregate combined in the proper ratios in a composite are known as asphalt concrete mix. The Marshall Method is often credited with creating this blend. The ASTM D1559 standard, published by the American Society for Testing and Materials, is followed in this approach, which involves testing a cylindrical bituminous specimen under loading conditions. Bituminous concrete is made by combining warmed stones with heated asphalt at a temperature of between 160 and 170 °C. In this investigation, heated aggregate is combined with shredded plastic that has been sieved through a retained IS filter measuring 600 × 2.36 mm. After being stored and coated for 24 hours, aggregate is combined with heated asphalt. The bitumen concentration for the samples ranges from 4.5% to 6.5%, with a 0.5% increase. 50 strikes are delivered on either side of the sample since this study's foundation is highways with moderate traffic. Prior to testing, the samples are kept in a water bath at 60 °C for 30 to 40 minutes. The maximum load is determined by the test's stability parameter.

Table 4.1 Plastic's properties

Types of material	Thickness (μm)	Softening point (°C)
Carry bags	10	110 – 130
PET bottles	130	120 – 130
Plastic packets	45	110 - 130

Table 4.2 Super-Bond A-99's properties (Opal Paints Products Pvt. Ltd.)

Sl. No	Property	Specification
i	Physical state	Liquid
ii	Color	Dark Brown
iii	Flash point	Above 180℃
iv	Pour point	Below 0℃

The test specimen is capable of withstanding that at a rate of 50.8 mm/minute loading. Three different plastic contents, 0.50, 0.75, and 1% by weight of the aggregate total are used to generate test samples.

4.5 Permeability Test

A material's capacity to permit fluid to pass through it is referred to as its porosity. The permeability test with a constant head is used to measure the permeability of the Marshall sample. In order to keep water from escaping throughout the test, a 100-thick plastic sheet is carefully wrapped around the circular sample. The edges of the sample are also covered with wax. The sample is only wrapped up to one-fourth of its height. A volume-measuring funnel is used to measure the sample's volume while submerged in water on a circular platform. A pan for collecting water is put underneath the sample. The volume of water that percolated through the sample is determined and plotted against time. The permeability coefficient is determined using Darcy's law. The standard experimental setup is displayed in Fig. 4.2.

4.6 Indirect Tensile Strength Test

The bituminous mixture's tensile characteristics and resistance to moisture damage are assessed using the Indirect Tensile Strength (ITS) test. The test is carried out according to ASTM D 6931. Both wet and dry materials are tested in this experiment. Wet samples are preconditioned at 60 °C for 24 hours. The specimens are then removed from the water bath and allowed to cool for two hours at a temperature of 25 °C. Samples that haven't been conditioned keep their temperature at 25 °C. They remained dry for the entire two hours. These samples are assessed using Marshall testing instruments. 51 mm/min is the rate of deformation for the test samples. The TSR is a gauge of moisture susceptibility and resistance. It is displayed as a ratio between the samples with and without water in terms of tensile strength.

Figure 4.2 Permeability Test setup in laboratory

4.7 Result and Discussion

Aggregate Test Results:

To determine the physical characteristics of uncoated and plastic-coated stone aggregates, several studies are conducted. These tests' outcomes are displayed in Table 4.3. In the table, it is observed that addition of plastic content has improved the overall properties of coarse aggregates.

Table 4.3 Characteristics of regular aggregate and aggregate with a plastic coating.

Name of the tests	Results				Specifications of IRC: 111-2009
	Normal Aggregate	% Plastic			
		0.50%	0.75%	1%	
Impact test (%)	23.28	22.73	22.18	21.84	Less than 24%
Los Angeles Abrasion (%)	29.54	26.63	25.12	24.17	Less than 40%
Specific Gravity	2.78	2.81	2.83	2.84	2.5-3.0
Water Absorption (%)	1.42	0.96	0.79	0.62	Less than 2%
Stripping Value	1.6%	0.8%	0	0	Less than 5%
Flakiness Index	19.35%	–	–	–	Maximum 35%
Elongation Index	15.28%	–	–	–	Combined
Crushing Strength (%)	18.47	17.82	17.25	17.13	Less than 30%

Test Result of bitumen:

Table 4.4 Properties of bitumen

Name of the tests	Test method	Results	Permissible value as per IS 73-2013
Penetration test	IS 1203-1978	69.2	60–70
Viscosity test	Bohlin Viscometer	0.547 Pa-s (135 °C) 0.212 Pa-s (165 °C)	–
Specific Gravity test	IS 1202-1978	1.03	1.01–1.06

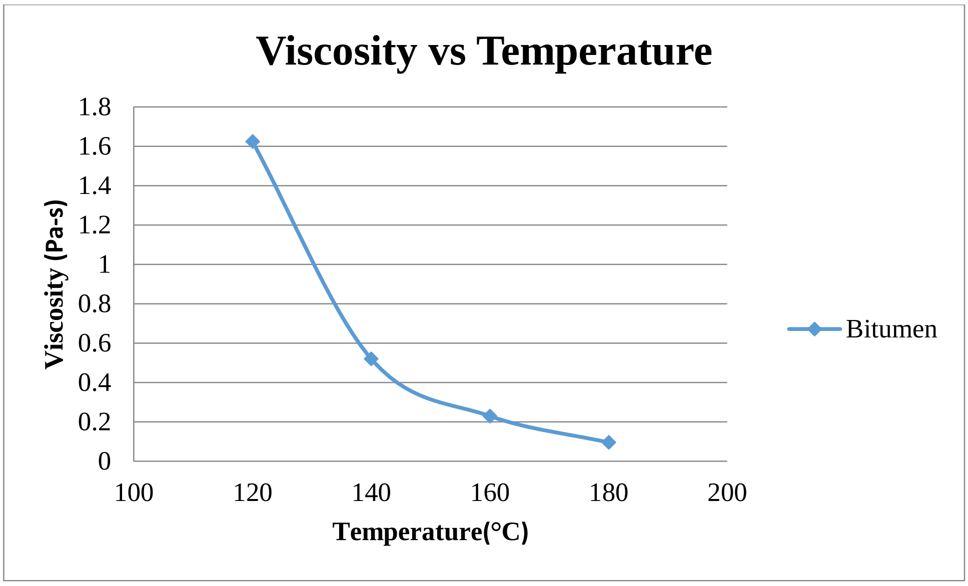


Figure 4.3 Viscosity variation of bitumen with temperature

4.8 Marshall Test Results

Marshall Samples were created using the NAPA (National Asphalt Pavement Association) gradation, which is depicted in Table 4.5.

Marshall samples are made using three different ratios of regular aggregate and plastic-coated stone aggregate, namely 0.50%, 0.75%, and 1%. (Table 4.6 and Fig. 4.3).

Table 4.5 NAPA gradation for preparing mix

Sieve (mm)	% passing by weight of specimen	Cumulative % passing	Cumulative % retained	% of aggregate and mineral filler
19	100	100	0	82.5 (Coarser fraction)
12.5	85–100	92.5	7.5	
9.5	55–75	65	35	
4.75	10–25	17.5	82.5	
2.36	5–10	7.5	92.5	14.5 (Finer fraction)
0.075	2–4	3	97	
Mineral filler				3

Table 4.6 Marshall Test results

S.L. No	Parameter	Normal Aggregate	% Plastic		
			0.5%	0.75%	1%
i.	OBC%	5.42	5.38	5.38	5.36
ii.	Marshall Stability(kN)	7.09	9.11	8.45	8.29
iii.	Flow(mm)	2.83	2.95	3.22	3.24
iv.	Unit weight (gm/cc)	2.16	2.17	2.172	2.178
v.	% Air void	17	16.5	16	16
vi.	%VMA	26.98	26.46	26.23	25.95
vii.	%VFB	42.45	40.94	40.58	39.84
viii.	Marshall quotient(kN/mm)	2.51	3.12	2.64	2.57

From the aforementioned test findings, it is clear that the plastic-mixed porous asphalt concrete is significantly more stable than the standard porous asphalt mix. Marshall Stability for normal mix and all three plastic contents met the requirement of medium traffic load conditions. The maximum Marshall stability is 9.11 kN with 0.50% plastic content. The results for stability at 0.75% and 1% plastic content were 8.45 kN and 8.29 kN, respectively. The Marshall quotient for products with 0.50% plastic content is estimated to be 3.12, which is likewise much higher than the average. Therefore, the optimal plastic content (OPC) for covering stone aggregates in this investigation is assumed to be 0.50%. Compared to a typical porous mix, the stability of this mixture has increased by 28.58%. The visual representations of the fundamental relationships between bitumen content and Marshall Stability, Flow value, Air void, MA, and VFB are shown in Figures 4.4, 4.5, 4.6, 4.7, 4.8, and 4.9, respectively. In the figures, it is observed that with the increase in plastic content all the parameters were influenced and tend to improve the results (X. Cui et al., 2017).

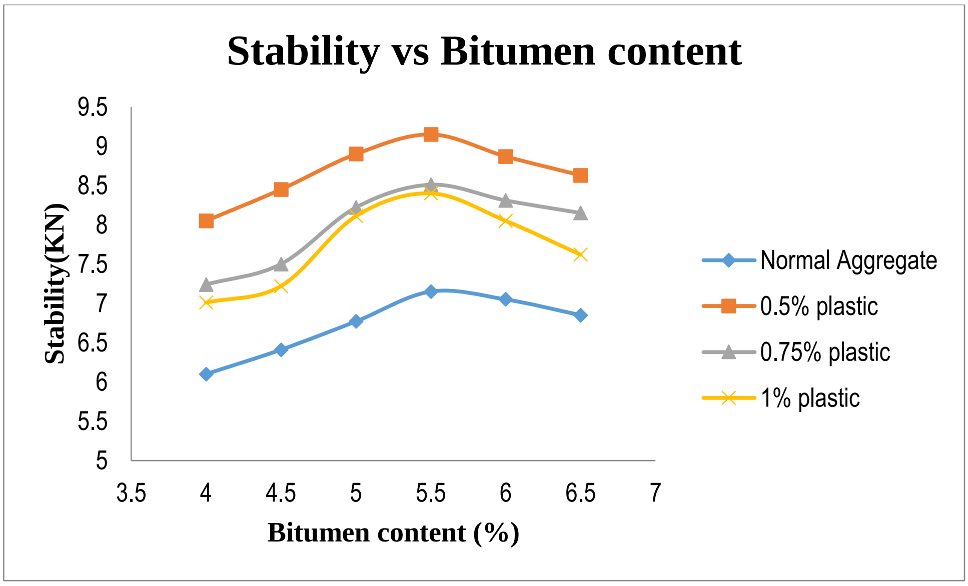


Figure 4.4 Marshall Stability of normal and PCA mix at different binder content

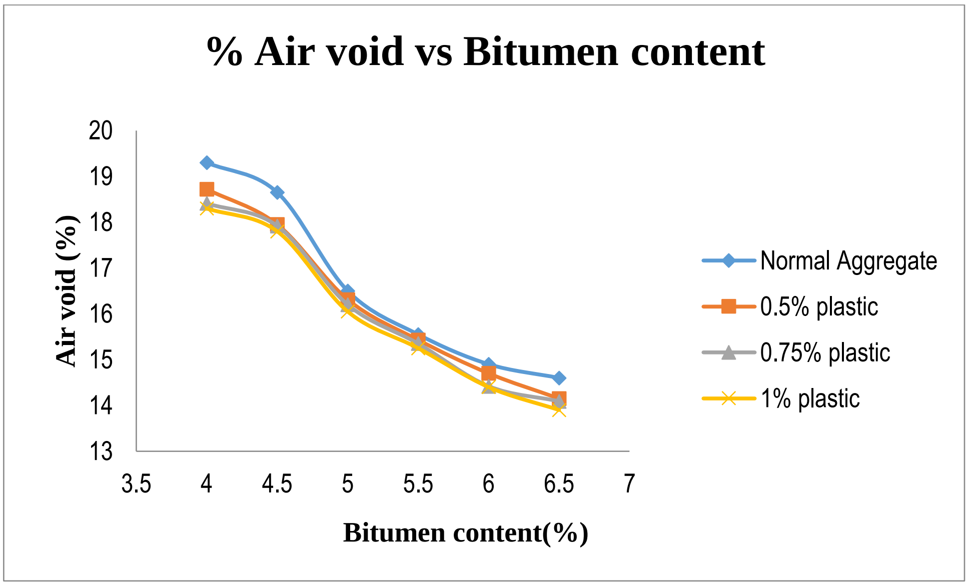


Figure 4.5 % Air void of normal and PCA mix at different binder content

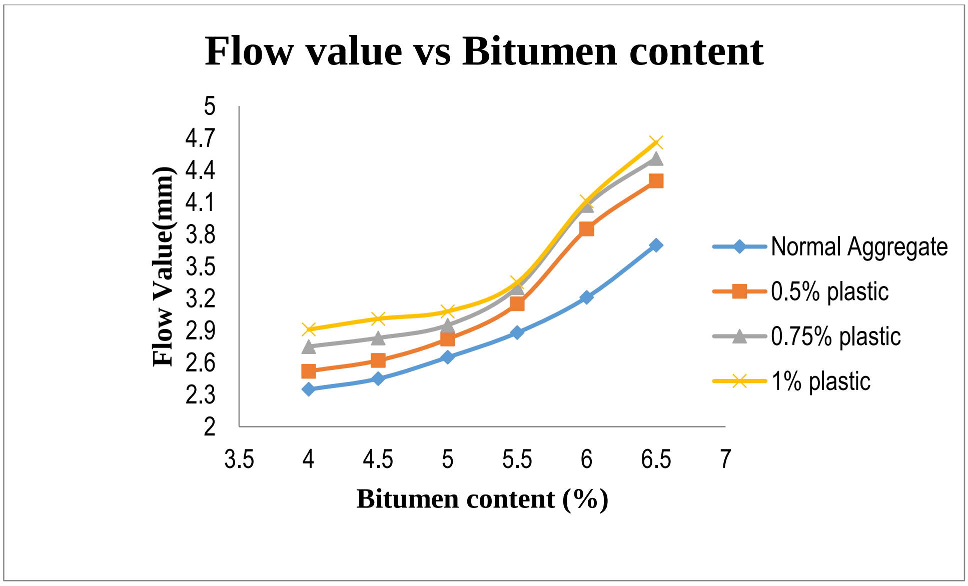


Figure 4.6 Flow value of normal and PCA mix at different binder content

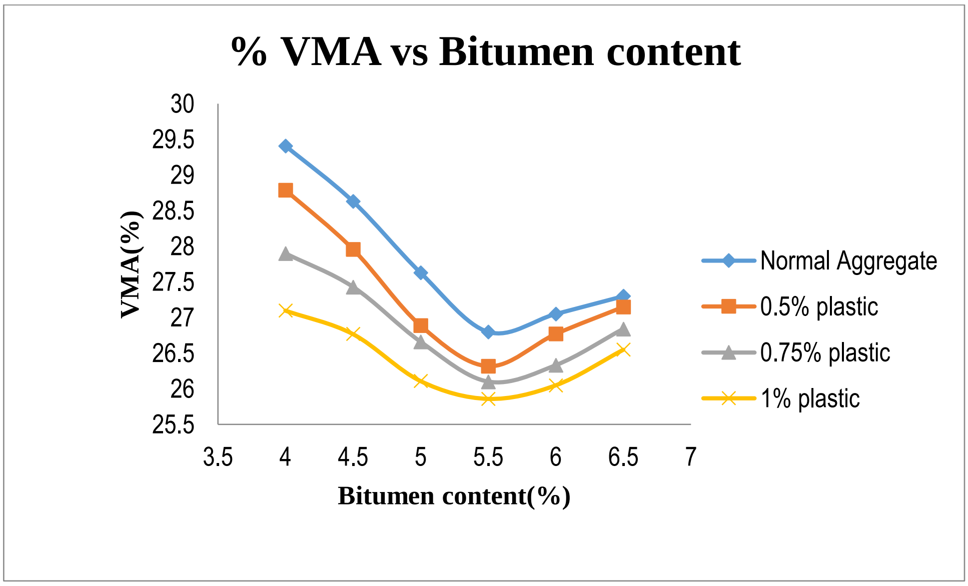


Figure 4.7 VMA of normal and PCA mix at different binder content

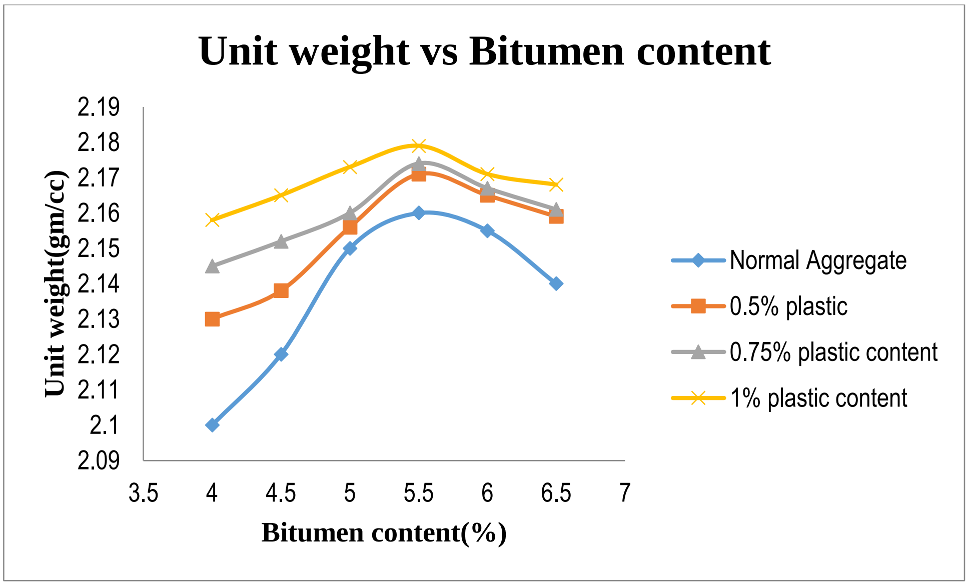


Figure 4.8 Unit weight of normal and PCA mix at different binder content

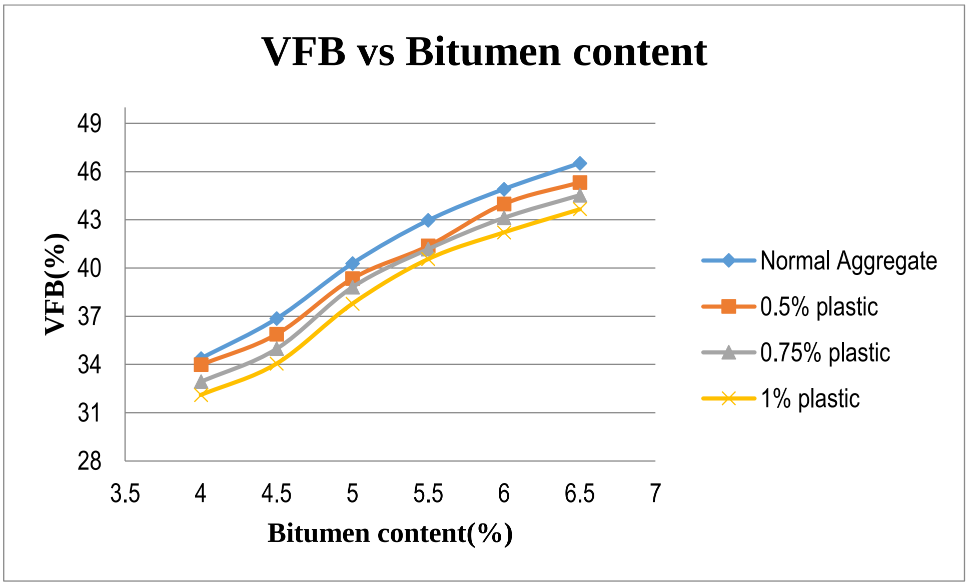


Figure 4.9 VFB of normal and PCA mix at different binder content

4.9 Permeability Test Results

Both regular and modified plastic samples are tested for permeability. To get the appropriate findings, Marshall Samples are generated with the relevant Optimum Binder composition (OBC) for each plastic composition. Test outcomes are displayed in Table 4.7 (Figure 4.4). With the increase in plastic content, permeability of the mix was reduced to improve the density of the mix (I. N. Grubeša, 2018).

4.10 Indirect Tensile Strength Test Result

The ITS test is conducted on materials that have been both wet and dry. An anti-stripping chemical (Superbond A-99) in the quantity of 0.1% by weight of binder is also used to assess the susceptibility to moisture. The test outcomes are represented visually in Figure 4.5. The result shows that addition of plastic content improves the strength of the mix and TSR value also improved at appropriate plastic content (X. Ma, 2018).

Table 4.7 Permeability test result

Plastic content (%)	Permeability (cm/s)
0	0.672
0.50	0.588
0.75	0.532
1	0.496

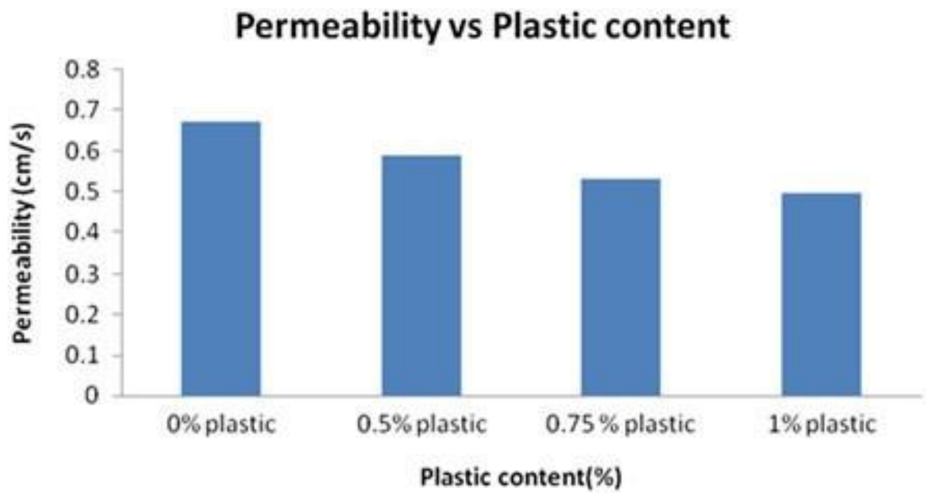


Figure 4.10 Comparison of permeability values for different plastic content

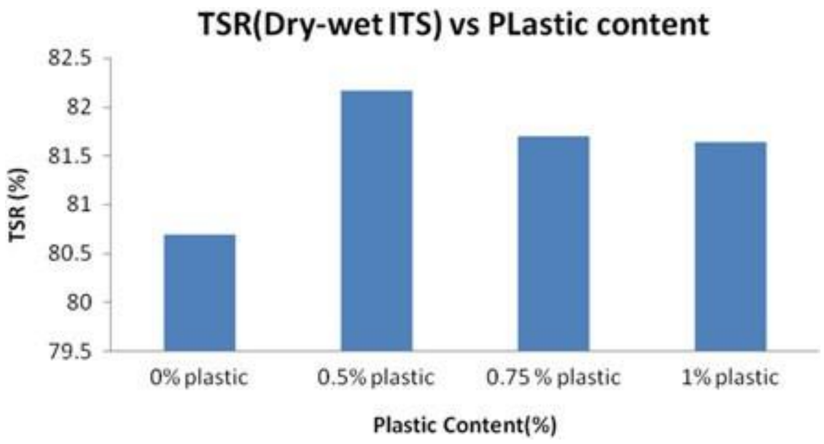


Figure 4.11 Comparison of TSR values for different plastic content

An indirect tensile strength test is carried out on both condition and unrestricted materials. A dosage of 0.1% by weight of the binder component of the anti-stripping chemical Super-Bond A-99 is also used to assess the moisture susceptibility of the material. The findings of the dry-wet and freeze-thaw ITS are shown below.

4.11 Dry-Wet ITS

Dry ITS and wet ITS tensile strength is found out by an equation provided in the earlier chapter and Tensile Strength Ratio (TSR) is a measurement of strength of unconditioned (dry) sample to strength of conditioned (wet) sample.

Table 4.8 Results of dry-wet ITS

Plastic content (%)	Dry ITS strength (kPa)	Wet ITS strength (kPa)	TSR (%)
0	315.23	254.36	80.69
0.50	320.25	263.12	82.16
0.75	331.37	270.74	81.70
1	336.13	274.45	81.64

According to the test findings mentioned above, both dry and wet samples' tensile strength improves as plastic content rises. Tensile Strength Ratio (TSR) at optimum plastic content i.e. 0.50% plastic content is found to highest at 82.16%. TSR value at 0.75% & 1% plastic content is observed as 81.70% & 81.64% respectively which are quite similar. TSR value has improved by roughly 1.82% with 0.50% plastic content. The test findings are graphically represented in the following manner:

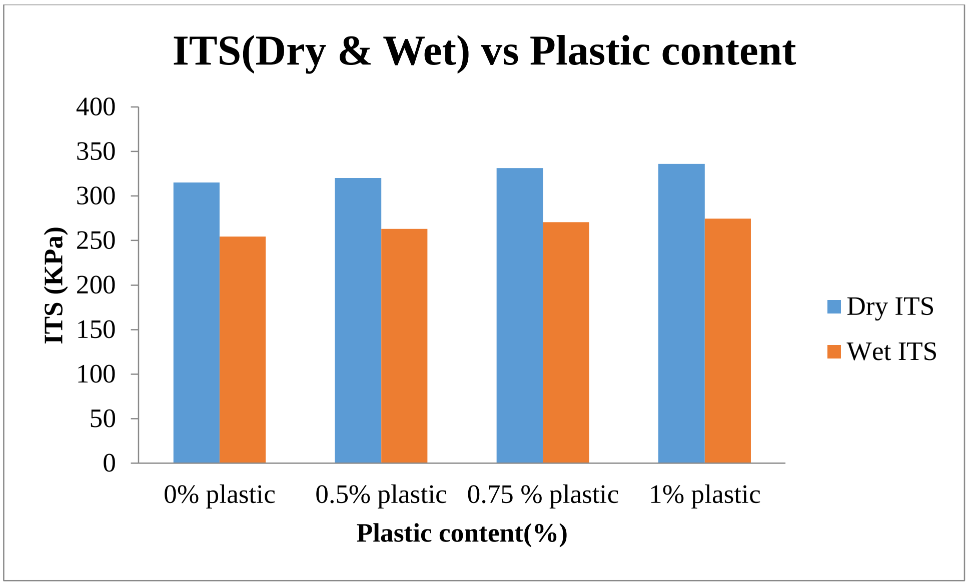


Figure 4.12 Comparison of Dry & Wet ITS for different plastic content

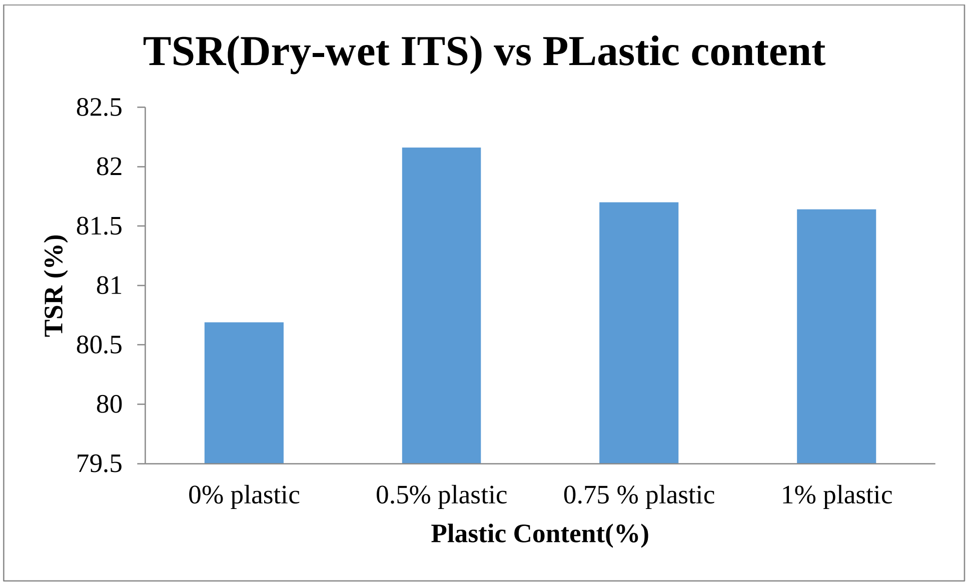


Figure 4.13 Comparison of TSR (Dry-wet ITS) for different plastic contents

4.12 Freeze-thaw ITS

The same equation used to determine tensile strength for dry-wet ITS is utilized to determine tensile strength for freeze-thaw ITS. Tensile Strength Ratio (TSR) is a measure of the strength of wet (freeze-thaw) samples compared to the strength of dry samples.

Table 4.9 Results of freeze-thaw ITS

Plastic content (%)	Dry ITS strength (kPa)	Freeze-thaw ITS strength (kPa)	TSR (%)
0	315.23	246.25	78.12

0.50	320.25	259.88	81.14
0.75	331.37	266.59	80.45
1	336.13	270.05	80.34

Test results show that the tensile strength of freeze-thaw ITS has decreased as compared to wet ITS. Therefore, the tensile strength ratio (TSR) value has also decreased in this case. TSR value at optimum plastic content, i.e., 0.50% plastic content, is highest at 81.14%. Polymer composition at 0.50% TSR has grown by around 3.86%. The test findings are shown graphically in the following manner:

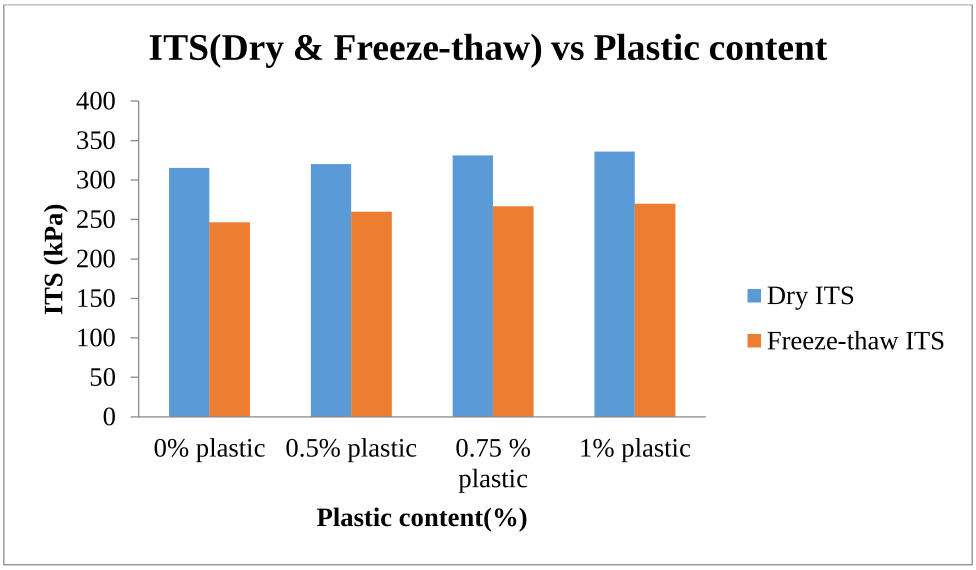


Figure 4.14 Comparison of Dry & Freeze-thaw ITS for different plastic content

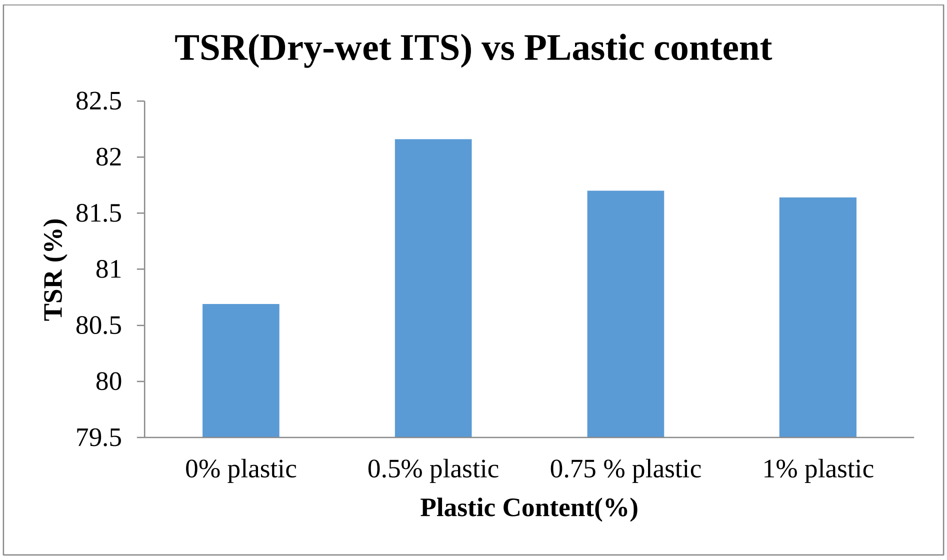


Figure 4.15 Comparison of TSR (Freeze-thaw ITS) for different plastic contents

4.13 Findings of the study

Compared to traditional asphaltic paving, porous bituminous pavement is weaker. In order to employ the porous bituminous mixture under medium traffic circumstances, this study aims to increase its strength while controlling its permeability. The inquiry and test results for regular and plastic-modified asphalt mixtures can be used to deduce the following:

- Results of aggregate tests reveal that the impact, abrasion, absorption, and stripping values have decreased as plastic content has increased.
- Plastic content between 0.75 and 1% has a zero-stripping value, demonstrating improved resistance to moisture susceptibility.
- By weight of aggregate, the optimal binder content (OBC) is discovered to be 5.39%, and it is determined that the aggregate's optimal plastic content (OPC) is 0.50% by mass. The greatest Marshall stability as well as Marshall Quotient are 9.10 kN and 3.10, respectively, at 0.50% plastic content. In comparison to a normal mixture, stability rose by 28.53% with a 0.50% plastic concentration.
- As the amount of plastic in the bituminous mixture increased, it became less permeable. At 1% plastic concentration, permeability is 0.496 cm/s, which has decreased to 26.19% from the usual mixture. Water can nonetheless soak through the pavement's structure and into the subgrade since there is significant permeability.
- The dry-wet ITS TSR value was increased by utilizing plastic-modified mix instead of regular mix. The greatest TSR value of 82.16% is recorded at 0.5% plastic material. Therefore, 0.50% plastic material exhibits superior resistance to moisture.

CHAPTER- 5

IMPROVEMENT OF STRENGTH USING CRUMB RUBBER IN POROUS ASPHALT CONCRETE

5.1 General

Urbanization and industrialization have been accelerating rapidly due to the overall growth of civilization and the increase in population throughout the world. Continuous deforestation and encroachment on forested land and rural areas for the sake of urbanization and industrialization are on the rise. As a result, the process of urbanization has a doleful effect on the environment and leads to the rise of deforestation. For instance, the construction of roadways, railways, airports, commercial buildings, etc. is covering a considerable track of open land with non-porous concrete construction, disrupting the free flow of surface water to reach the underground water table. As a result, a huge quantity of rainwater cannot percolate through the non-porous surface, which leads to water logging. Porous pavements are the opposite of conventional densely graded flexible pavement, which allows water to pass through the voids inside the pavement surface. Porous pavements have an open-graded design, which is responsible for the percolation of water.

Porous asphalt (PA) is a mixture of asphalt with reduced fines. The reduction in fines forms a pervious structure that permits water to drain through it, which generally has at least 16% voids and is used successfully in regions with heavy rainfall. Open-graded friction course (OGFC) bituminous mix is a type of porous pavement that has been used to improve the pavement surface's ability to resist skidding.

The elevated percentage of voids enhances safety by reducing the influence of skidding and enhancing the riding quality of the pavement surface under wet weather conditions. In addition to all the advantages of PA, past experimental studies have revealed several mechanical and performance shortcomings. This study has been emphasized to enhance the characteristics of the OGFC bituminous mix by using crumb rubber. It has also been taken care of that the void percentage required for water percolation be maintained properly.

Rubberized asphalt binder is a material consisting of asphalt binder and crumb rubber. An environmentally friendly technology that is extensively researched and employed in the pavement industry is recycled tire rubber. Previous field experiences show that the rubberized asphalt binder added with HMA can improve the durability and resistance properties of pavement surfaces to rutting. Therefore, in this study, it has also been studied about the appropriate percentage of crumb rubber to be added with OGFC for improved strength when used on medium-traffic roads.

One potential answer to the serious issue of water table reduction is porous bituminous pavement. Through the passage of rainwater among many layers into the soil subgrade, porous bituminous pavement refills the groundwater table (Soni and Goyel, 2017). A typical cross section of porous asphalt pavement with different layers and an underdrain piping system is given in Fig. 5.1. The result finds that the RPA gives the desired stability value at 1% crumb rubber content with 5% OBC, which is considerably higher as compared to conventional PA mixes.

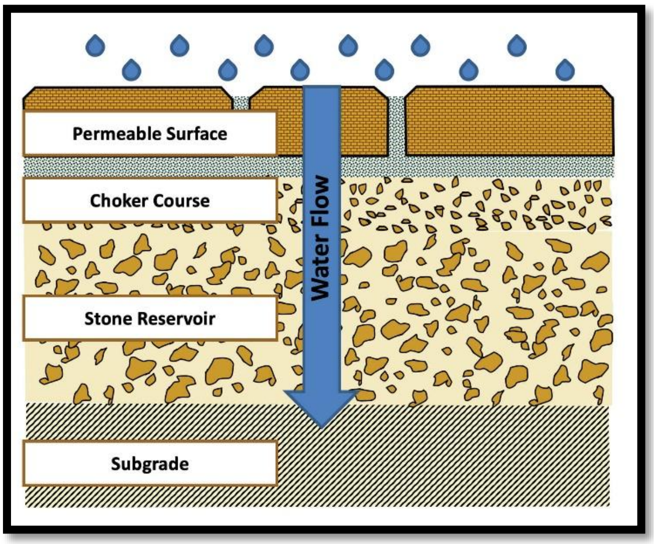


Figure 5.1 Typical cross section of porous asphalt pavement

[Source: https://landscapeontario.com/paving-the-future]

5.1.1 Objectives

Primary objectives of this work are as follows: -

- To enhance the characteristics of OGFC bituminous mix by using crumb rubber without losing the void percentage required for water to percolate.
- To look for an appropriate combination of crumb rubber in bituminous mix, which will be strong enough to use in medium to heavy traffic volume road under feasible condition.

5.2 Materials and Methodology

5.2.1 Materials

According to numerous studies, the state of the surrounding environment, the country's financial situation, and the needs of its citizens all have a significant impact on the pavement design, resulting in distinct standards for each country. In India, pavement design methods and material qualities are commonly assessed using the IS and IRC codes. It is customary in India to design pavement using traditional materials. Various tests relating to the characteristics of traditional materials, including bitumen, aggregate, and filler material, have been shown in this chapter. Additionally, various advanced studies, like Marshall, ITS, Permeability, and others, are also displayed in the chapter's final section. A list of materials that are used in these studies is given below:

1. Stone aggregates acquired from local suppliers.
2. Normal VG-30 Bitumen.
3. Crumb Rubber (manufactured by Arhaint Exim Corpuration, New Delhi).
4. Nano-Silica (manufactured by Astrra Chemicals, Chennai).

5.2.1.1 Aggregate

The stone aggregate used in this study was collected from a local dealer near NIT Agartala. Aggregate is generally used as a binder as well as a filler material, which imposes strength on the road. The aggregate gradation for porous asphalt pavement is taken according to the NAPA (National Asphalt Pavement Association), which satisfies the requirements of IRC 111-2009.

Table 5.1 Adopted NAPA graduation for OGFC bituminous mixture

Sieve size (mm)	% passing by weight of specimens	Cumulative % passing	% retained	% of aggregate & filler material
19	100	100	0	Coarser fraction 82
12.5	100-85	92	8	
9.5	55-75	65	27	
4.75	10-25	18	47	
2.36	5-10	8	10	Finer fraction 15
0.075	2-4	3	5	
Finer				3

5.2.1.2 Bitumen

In this study VG-30 grade bitumen are used. Bitumen are generally used as a binder in the bituminous concrete mixture. Basic property test of the bitumen has done to determine its compatibility.

5.2.1.3 Crumb rubber

Crumb Rubber is the rubber in the form of powder made from scrap & used worn out tyres. Old used and scrap tyres are available in huge quantities in every country and almost it has no use. Since there is no such alternative use of scrap and used tyre, so in this investigation, open graded bituminous mix's characteristics are enhanced by the use of shredded Crumb Rubber powder. The prescribed properties claimed by the manufacturer of Crumb rubber are following:

Table 5.2 Properties of crumb rubber.

SL. No	PARAMETERS	TEST CONDITIONS	UNIT	STANDARD SPECIFICATION
i	Acetone extraction		%	5-10
ii	Ash content	825+/25C/1 hr	%	Max 20
iii	Bulk Density		gm/cc	1.15 to 1.3
iv	Sieve Analysis		%	400-600 µ

(N.B- These properties are claimed by the manufacturer of Crumb Rubber and Nano-Silica, in this study attempt has been made to check the feasibility of applying these materials with bituminous concrete mixture to study the effectiveness of these materials on property improvement.)

5.2.2 Methodology

As a first phase, the physical and mechanical characteristics of bitumen and stone aggregate are individually assessed. The following tests were carried out to determine the fundamental characteristics of stone aggregate:

- **Specific Gravity & Water Absorption (conforming to IS 2386: Part III-1963)**

By dividing a solid's mass by the mass of an equivalent volume of pure water at a specified temperature, its specific gravity can be calculated. The strength or material quality of stone aggregate is gauged by its specific gravity. Since aggregates have permeable voids, apparent specific gravity and bulk specific gravity are used as measurements of the specific gravity of aggregates. Apparent and bulk specific gravities, and their differences depend on how many water-permeable gaps are present in the aggregates. The hardness of a rock can be determined by how much water it can absorb. High water absorption makes stone more porous by nature, making it generally inappropriate unless it is determined that it is suitable depending on strength, impact, and hardness.

- **Shape test (conforming to IS 2386: Part l)**

The amount of flakiness and elongated particles in an aggregate can be used to determine its form. The weighted percentage of aggregate particles is the definition of the flakiness index, whose smallest dimension is less than three-fifths of their mean size. Following the flakiness index test, the flaky particles are removed from the aggregate mass, and the non-flaky particles are used in the elongation test. The proportion of aggregate particles by weight whose smallest dimension is smaller than 1.8 times their mean size is known as the elongation index.

- **Abrasion test (conforming to 1S 2386: Part IV-1963)**

Aggregate hardness is assessed using an abrasion test. The best method for measuring the hardness attribute is the Los Angeles abrasion test, which India has adopted as a standard. The main goal of this test is to gauge how much wear happens when steel balls employed as an abrasive charge come into contact with the aggregate's particles. Depending on the grade of the sample, a cast iron abrasive charge with a 48-millimeter diameter and a weight of 340–445 g is added to the aggregates. A 5–10 kg sample of aggregate is required for this, and after between 500 and 1000 drum revolutions, the aggregates are passed through a 1.7 mm sieve; the percentage of the aggregates that pass through the sieve is then represented as a percentage of wear by the weight of the entire sample.

- **Crushing Strength Test (conforming to 1S 2386: Part IV-1963)**

This is one of the crucial technical requirements for a road stone. The aggregates' ability to withstand crushing brought on by moving vehicles, which is a stress brought on by moving vehicles, is measured by the test. Additionally, the aggregates must be sturdy enough to resist crushing beneath construction rollers and beneath vehicles' tough tire rims hauled by heavily loaded animals.

The crushing values for aggregate give a comparative indication of the aggregate's resistance to crushing under a compressive load that is gradually applied. Low crushing values for aggregate are preferred in order to produce pavement aggregate of the highest quality. According to IS and IRC, aggregates used in concrete other than for wearing surfaces should not have an aggregate crushing value greater than 45%, and coarse aggregates used in cement concrete pavement shouldn't have one greater than 30%.

- **Impact value test (conforming to IS 2386: Part IV-1936):**

The road aggregates are exposed to impact or pounding action during the construction process of pavement layers, notably compressed by large rollers and also owing to the movements of heavy commercial vehicles, and there is a risk that some stones will break into smaller fragments. Therefore, the stone aggregate needs to be sufficiently resistant to withstand fracture under quick impact loads. To ascertain the impact resistance or toughness of aggregates, an impact test is therefore conducted. The device for testing aggregate impact is made up of a metal base and a cup with a 50 mm depth and 102 mm interior diameter, a cylindrical, 13.5–14 kilogram metal hammer that falls naturally from a height of 380 mm. Three layers of aggregate, which have been hammered 25 times with a tamping rod after going through a 12.5-millimeter screen while remaining on a 10-millimeter sieve, are placed within the cylinder. Aggregate impact resistance is determined by dividing the proportion of crushed aggregate that passes the 2.36 mm screen by the sample's overall weight.

Figure 5.2 Impact Testing Machine.

Figure 5.3 Los Angles Abrasion Testing Machine

To ascertain the fundamental characteristics of bitumen, the following experiments are carried out:

- **Specific Gravity (conforming to IS 1202- 1978):**

The primary characteristic of bituminous binders that is usually used to categorise them for use in paving projects is their specific gravity. For mix design, the specific gravity value is also helpful. Bitumen's specific gravity is calculated using the pycnometer method. The relative density of pure bitumen is between 0.97 and 1.02 when measured at a temperature of 27 °C.

- **Viscosity test (Bohlin Viscometer)**

Due to internal friction, bitumen's viscosity provides flow resistance. Any liquid's ability to flow under an applied force depends on its viscosity; the higher the viscosity, the slower the flow or movement will be. In a laboratory, the shear between rotating coaxial cylinders and hot bitumen is used to calculate the coefficient of absolute viscosity, which represents the proportion of applied shear stress to shear rate.

- **Penetration Test (conforming to IS 1203-1978)**

The penetration test provides an indirect indicator of bitumen hardness. At 27°C, with a load of 100 g and a load application period of 5 sec, it gauges how deep a typical needle can go, which will pierce a sample of material. 1/10 mm is the unit of penetration. Bitumen can be categorized based on consistency using penetration limits, and popular grades include 30/40, 60/70, and 80/100.

The rubber powder known as "crumb rubber" is created from discarded and trashed tires. For every nation, the growing disposal of old, used, and scrap tires poses a serious concern. Due to the lack of an alternative application for waste and used tires, this study employed shredded Open-graded bituminous mixes are given better qualities by the inclusion of crumb rubber powder. With the chemical formula SiO_2, silicon dioxide, sometimes referred to as nano-silica, is an oxide of silicon and is most often found in quartz and various living things in nature. Silica makes up the majority of sand in various regions of the world. Nanosilica has also been used in this study as a bitumen modification. Table 5.3 displays the nanosilica manufacturer's claimed recommended qualities.

Table 5.3 Properties of Nano Silica (Reproduced by Astra Chemical)

Test Item	Standard Requirements	Test Results
Specific Surface Area(m^2/gm)	200 + 20	201
pH Value	3.7 – 4.5	4. 15
Loss On Drying @ 105 Deg.C (5)	< 1. 5	0. 45
Loss On Ignition @ 1000 Deg.C (%)	< 2.0	0.69
Sieve Residue (5)	< 0. 04	0. 02
TAMPED DENSITY G/L	40 – 60	43
SiO_2 CONTENT (%)	> 99. 8	99. 90
Carbon Content (%)	< 0. 15	0. 06
Chloride Content (%)	< 0. 0202	0. 008
Al_2O_3	< 0. 03	0. 005
TiO_3	< 0. 02	0. 004
Fe_2O_3	< 0. 003	0. 001
Specific Gravity	2. 2 – 2. 4(Generalised)	
Particle Size	17 Nano	

- **Permeability test**

Permeability is a property of porous asphalt pavement that allows water to pass through the pores present in the pavement structure. In this study, the Marshall sample's permeability is calculated by the falling head pearability method. The set-up consists of a Marshall sample, a circular coller, a volume measuring funnel, a thin plastic sheet of 100 microns, a seal tap, mesh, and wax. At first, the plastic sheet is wrapped around the Marshall sample up to 1/3 of its length and taped carefully. Additionally, wax is wrapped around the edges of the sample. With a volume measurement funnel, water was poured while the sample was wrapped and placed over a circular collier with a mesh. A steel pan is provided at the bottom of the setup to collect the perculated water. A typical picture of the setup is shown below.

Figure 5.4 Falling head permeability test set up

5.2.2.1 Sample Preparation

The mix design is done by Marshall's Mix design approach, with binder content ranging from 4 to 6.5% by aggregate weight. Along with these three combinations of crumb rubber (0.5%, 1%, and 1.5% by weight of aggregate). In this research, locally available aggregate with selected grading is heated to 1800°C and then shredded into crumb rubber of size 0.5 to 0.3 mm has been added to the heated aggregate and mixed properly for 2 minutes before adding the binder. The binder, heated to 1600°C, is added for the preparation of the sample.

5.2.2.2 Marshall Method of Mix Designs

The Marshall method is frequently used to test asphaltic concrete mixtures. This technique can be used to gauge the bituminous mix's stability and flow value. The Marshall technique of bituminous mix design has two key components: (i) Density-void analysis and (ii) Stability-flow test. In this study, Open-graded bituminous concrete and concrete modified with Crumb rubber have been investigated.

For medium-volume roads, Marshall Samples are prepared by giving 50 blows to each face of the hot bituminous concrete mix. A total of 90 cylindrical specimens (dia 101.6 cm, average height 680 mm) are prepared to evaluate the volumetric properties.

This study has examined open-graded bituminous concrete as well as concrete that has been treated with crumb rubber and nanosilica. To assess the volumetric qualities, 100 cylindrical specimens with average heights of 680mm and a diameter of 101.6mm were constructed.

Volumetric properties

The volumetric properties of compacted specimen are determined considering binder content versus stability, air voids (V_v), bulk density (G_m), voids filled with bitumen (VFB) and voids in mineral aggregate (VMA).

Air voids percentage, $\mathbf{V\nu} = \frac{G_t - G_m}{G_m} \times 100$

Here, G_m= Bulk density of specimen.

G_t = Theoretical mixture's specific gravity

$$\mathbf{G_t} = \frac{100}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_4}{G_4}}$$

Where, W_1= percent of the whole mix's course aggregate, by weight

W_2=percent by weight of fine aggregate in total mix

W_3= percent by weight of filler in total mix

W_4= percent by weight of bitumen in total mix

G_1=apparent specific gravity of coarse aggregate

G_2= apparent specific gravity of fine aggregate

G_3= apparent specific gravity of filler

G_4= Bitumen's apparent specific gravity

Percent void in mineral aggregate, **VMA**=V_v+V_b

Here V_v= volume of air voids, %

V_b= volume of bitumen, **V_b%** = $G_m \times \frac{W_4}{G_4}$

Percentage of voids filled with bitumen,$\mathbf{VFB} = \frac{100V_b}{VMA}$

Figure 5.5 Marshall Test sample

Figure 5.6 Marshall testing machine

5.3 Results and Discussions

General

The various test results from the thesis study and the data's associations with one another have been discussed in this chapter. This chapter focuses mostly on the findings of the Marshall Test in various test samples and the permeability of various Marshall samples. The crucial processes for assessing the different parameters in this chapter are listed below.

5.3.1 Test Results of Stone Aggregate

The Marshall Test is a significant experiment that must be carried out in order to do any kind of pavement design study, and selection aggregate is an essential component. To determine the quality of the aggregate to be utilized in various tests, the tests listed below are being conducted.

By performing the fundamental tests outlined in IS 2386 (Parts I–IV), the physical characteristics of stone aggregate were ascertained. The nearby NIT Agartala campus served as the source of the stone aggregate. The output of the properties test is shown in Table 5.4 below.

Table 5.4 Properties of stone aggregate

SL No.	Name of the Test	Test Method	Test Result	Specification of IRC: 111-2009
1	Specific Gravity	IS: 2386 Part III	2.761	2.5-3.0
2	Water Absorption		1.11%	Less than 2%
3	Impact Test	IS: 2386 Part IV	25.49%	Less than 24%
4	Los Angles Abrasion	IS: 2386 Part IV	16%	Less than 30%
5	Crushing Strength	IS: 2386 Part IV	28.5%	Less than 30%
6	Flakiness Index	IS: 2386 Part I	21.58	Maximum 35% Combined.
7	Elongation Index		19.35	

5.3.2 Test Result of Bitumen

In this project, the VG-30 grade bitumen has been used. Basic properties of bitumen as a binder are summarized in the given Table 5.5.

Table 5.5 Properties of bitumen

SL No.	Name of the Tests	Test Method	Test Result	Specification of IRC: 111-2009
1	Specific Gravity Test	IS: 1202-1978	1.03	1.01 – 1.06
2	Penetration Test	IS: 1203-1978	69.5	60-70
3	Viscosity Test virgin bitumen	Bohlin Viscometer.	0.552Pas (140 ^{0}C) 0.212Pas (160 ^{0}C) 0.0996Pas (180 ^{0}C)	-
4	Viscosity Test 2% NS added bitumen		0.612Pas (140 ^{0}C) 0.242Pas (160 ^{0}C) 0.111Pas (180 ^{0}C)	-

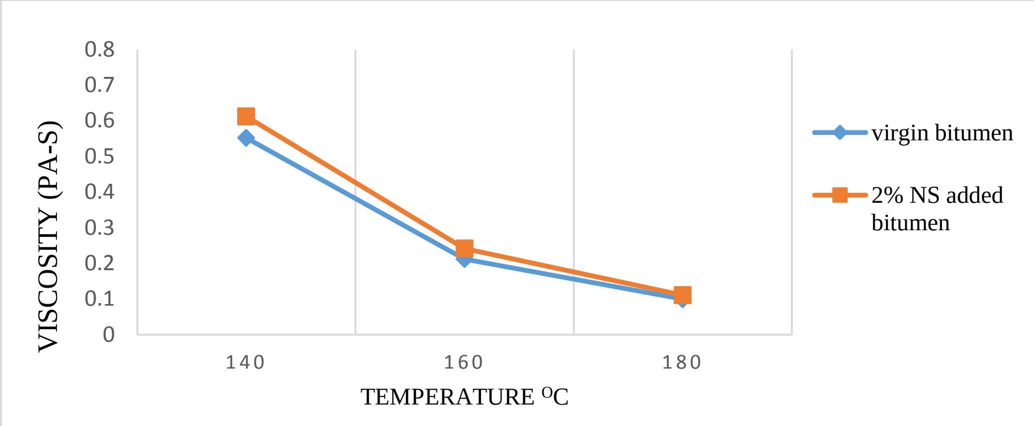


Figure 5.7 Variation of viscosity with temperature.

For preparing Marshall Sample, we are using OGFC gradation specified by National Asphalt Pavement Association (NAPA) given in table 5.6.

Table 5.6 Adopted NAPA gradation for OGFC bituminous mix

Sieve size in mm	% passing by weight of specimen	Cumulative % passing	% retained	% of aggregate and filler material
19	100	100	0	
12.5	100-85	92	8	
9.5	55-75	65	27	(Coarser Friction) 82
4.75	10-25	18	47	
2.36	5-10	8	10	
0.075	2-4	3	5	(Finer Fraction) 15
Finer				3

5.3.3 Design of Bituminous Concrete by Marshall Mix

In this research, both regular aggregate and aggregate heated with CR prior to applying the binder were used to prepare the Marshall Test sample. For normal aggregate, three sets of samples were prepared with binder content ranging from 4% to 6.5% of aggregate, with an increment of 0.5% of bitumen content by weight of aggregate. Similarly, with the CR-added aggregate, three sets of samples were prepared with CR content of 0.5%, 1%, and 1.5% by total weight of aggregate. For the Marshall Sample, 1100 g of stone aggregate of NAPA gradation has been used, which was adopted after preparing three trial mixes of 1200 g, 1100 g, and 1000 g and comparing the specimen height with the mould height. The results of these normal and CR-added aggregates are tabulated in Table 5.7.

Table 5.7 Marshall Test results of normal and CR modified OGFC mix

SL No.	Name of Parameter	Normal Mix	CR modified OGFC mix.		
			0.05%	**1%**	**1.50%**
1.	OBC%	6	5.63	4.92	4.53
2.	Marshall Stability (kN)	8.55	12.65	12.7	12.32
3.	Flow (mm)	4.14	3.5	2.9	2.31
4.	Unit Weight Gm/cc	2.05	2.10	2.07	2.046
5.	VMA%	29.3	29.1	26.8	27.33
6.	VFB%	39.3	38.3	34.5	31.22
7.	% Air Void	17.53	17.58	16.33	16.97
8.	Marshall Quotient (kN/mm)	2.08	3.8	4.6	5.35

Mixtures range in average unit weight from 2.03 gm/cc to 2.08 gm/cc, or 50 blows. The percentage of air voids is higher in porous asphalt pavement. Because a large amount of water will be able to percolate through it. The stability value should also be satisfactory in addition to the air void; otherwise, the pavement may fail. A minimum of 16% air vacancy is needed to make the pavement permeable, according to Kandal et al. As a result, for optimal bitumen calculation, bitumen content equivalent to 16% air void is taken into account rather than the 4% taken into account for standard pavement. The flow value range for conventional pavement is 2 to 4 mm, whereas porous asphalt pavement does not have a set flow value range. The flow value in this instance ranges from 2 to 5 mm. The stability value for porous asphalt pavement is typically substantially lower than the standard one. However, the primary goal of this study is to increase stability while maintaining the necessary air vacuum for low- to high-traffic roadways.

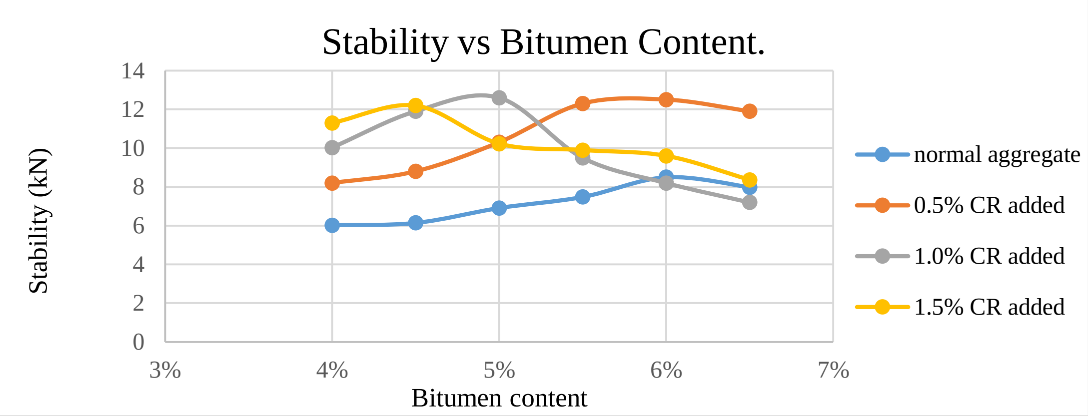


Figure 5.8 Marshall Stability of normal and RPA mix at different binder content

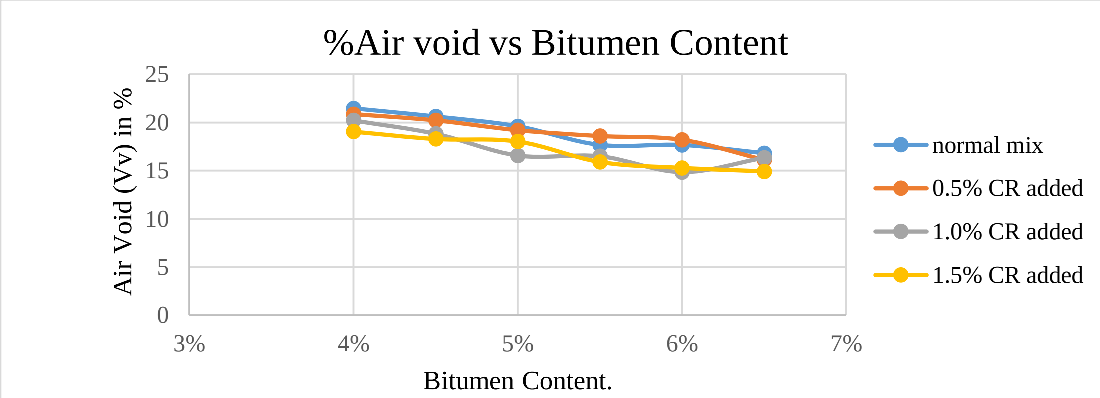


Figure 5.9 % Air void of normal and RPA mix at different binder content

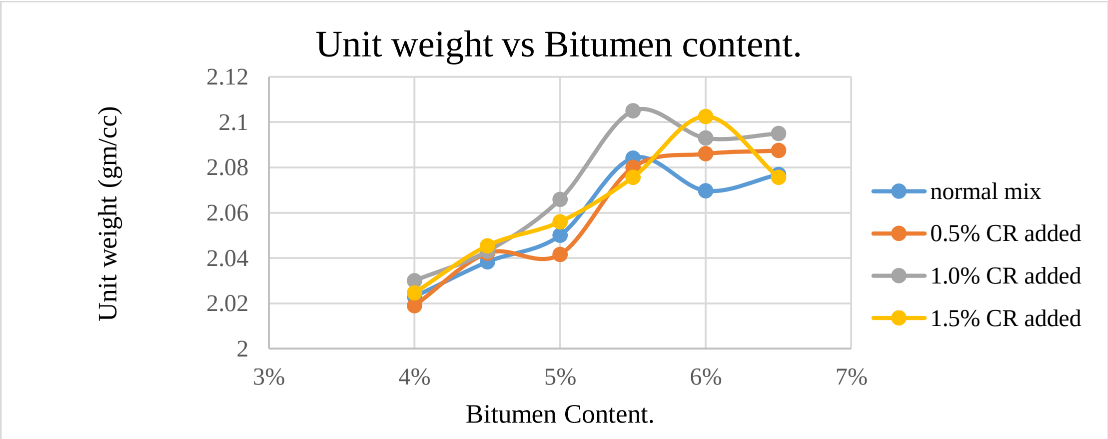


Figure 5.10 Unit weight of normal and RPA mix at different binder content

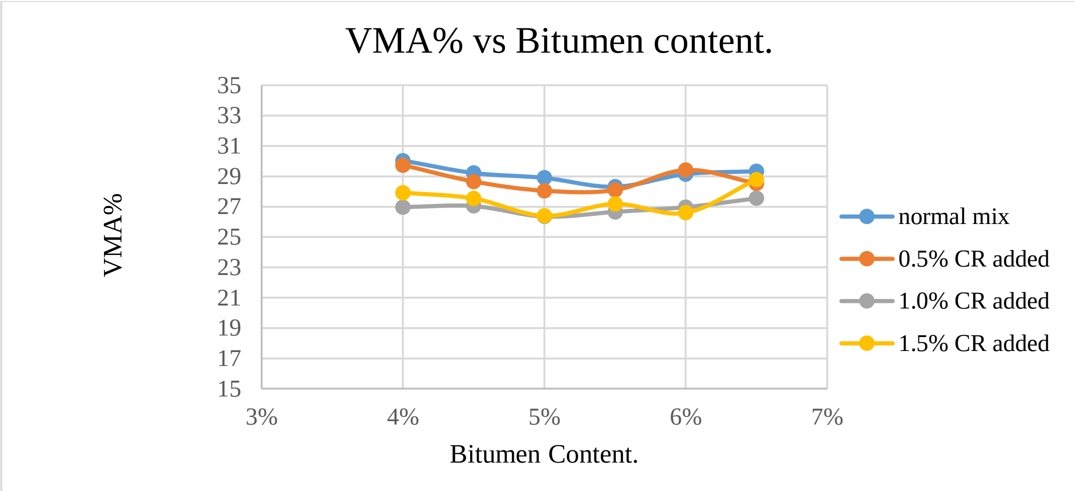


Figure 5.11 VMA% of normal and RPA mix at different binder content

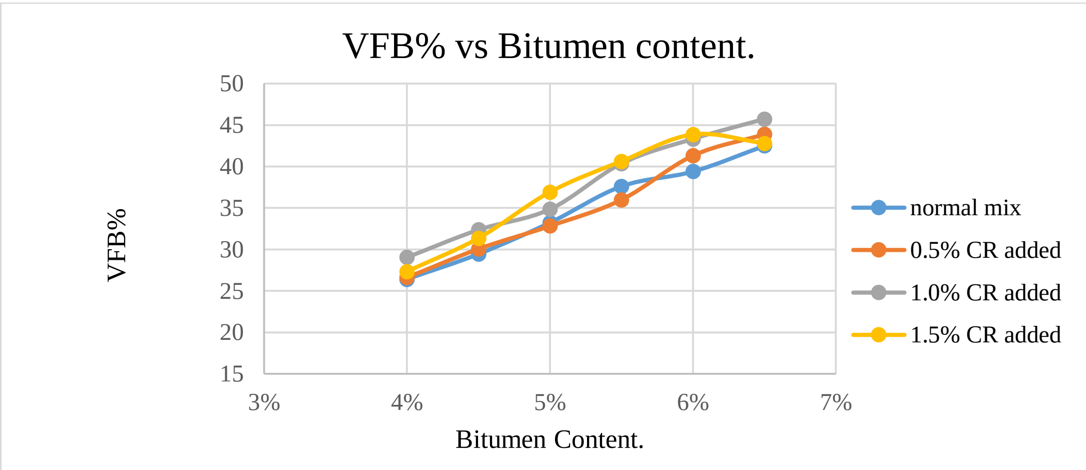


Figure 5.12 VFB% of normal and RPA mix at different binder content

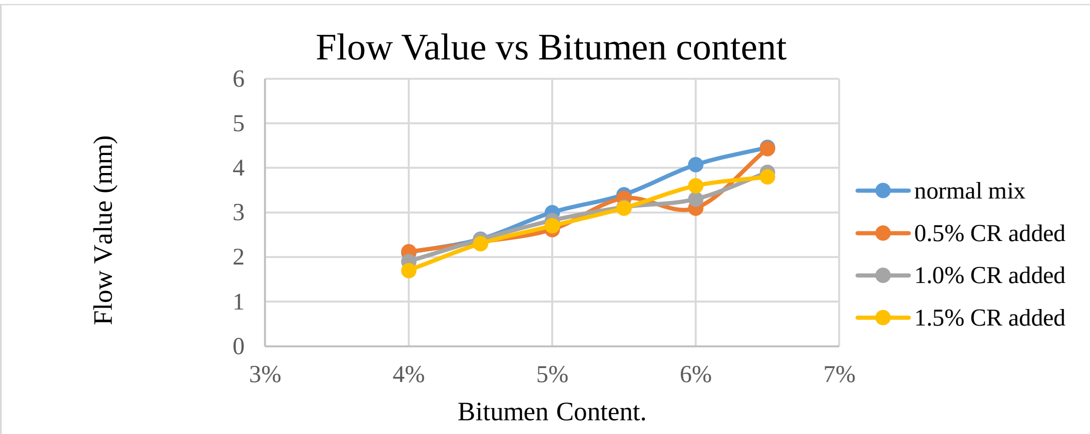
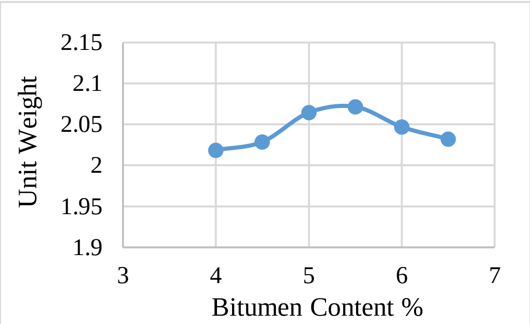


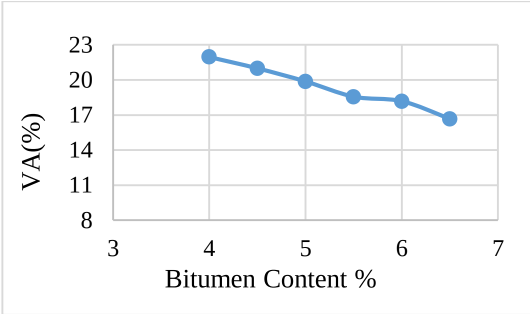
Figure 5.13 Flow Value of normal and RPA mix at different binder content

5.3.3.1 Marshall test of RPA added with 2% NS

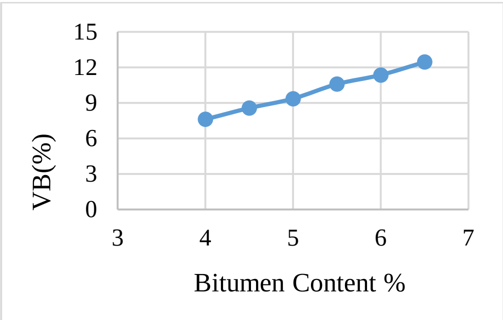
The Marshall Test results of the RPA mix were examined, and it was discovered that the RPA mix with 1% CR rubber content provides the greatest Stability value of around 12.7 kN. Additionally, RPA mix that contains 1% CR satisfies other requirements for porous asphalt. As a result, RPA mix with 1% CR content has been considered for future research. The test results are displayed in the graphs below:



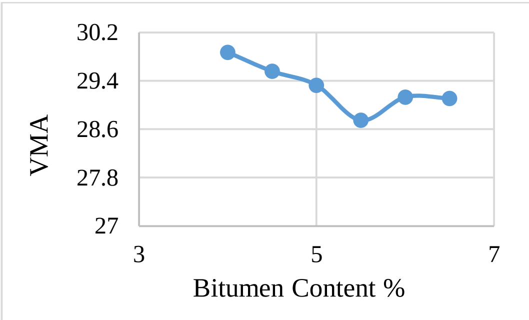
Unit wt. vs Bitumen content



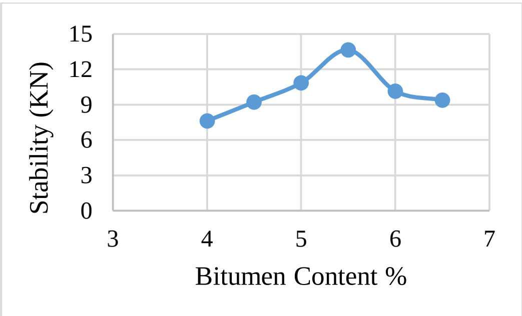
VA vs Bitumen content



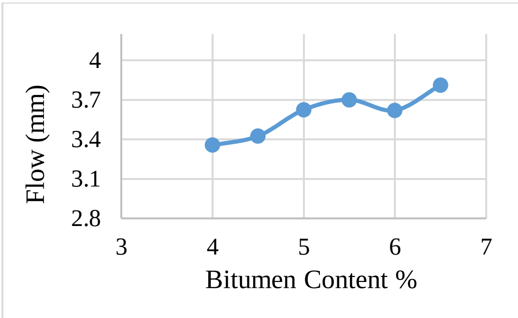
VB vs Bitumen content



VMA vs Bitumen content



Stability vs Bitumen content



Flow vs Bitumen content

Figure 5.14 Marshall Test of RPA added with 2% NS

The following table was created after analyzing the aforementioned graphs. It has been observed that, up until a certain degree, the stability value rises with increasing binder content before starting to fall. As a result, as the amount of binder material increases, the volume of the air void also begins to decrease. As can be seen from the aforementioned graphs, bitumen with a 5.5% percentage exhibits the best level of stability and satisfies the air void requirement. After figuring out the OBC value, the following table is created from the graph above. From the test results, it is observed that Crumb Rubber modified mix added with Nano Silica gives improvement in different parameters as compared to the unmodified mix (V. Khilari et al. 2017).

Table 5.8 Marshall Test results 2% NS added RPA mix.

SL No.	OBC	Marshall Stability (kN)	Flow (mm)	Unit Weight Gm/cc	VMA%	VFB%	%Air Void	Marshall Quotient (kN/mm)
1.	5.5	13.65	3.69	2.08	28.75	36.85	18.17	3.48

5.3.4 Permeability Test

Permeability tests are conducted by the falling head permeability method using a suitable set-up in the laboratory. 500 ml of water is poured into the test set-up, and the time required to fully percolate the water through the sample is measured. The coefficient of permeability is determined by using Darcy's law. The test results for different test samples are given in Table 5.9.

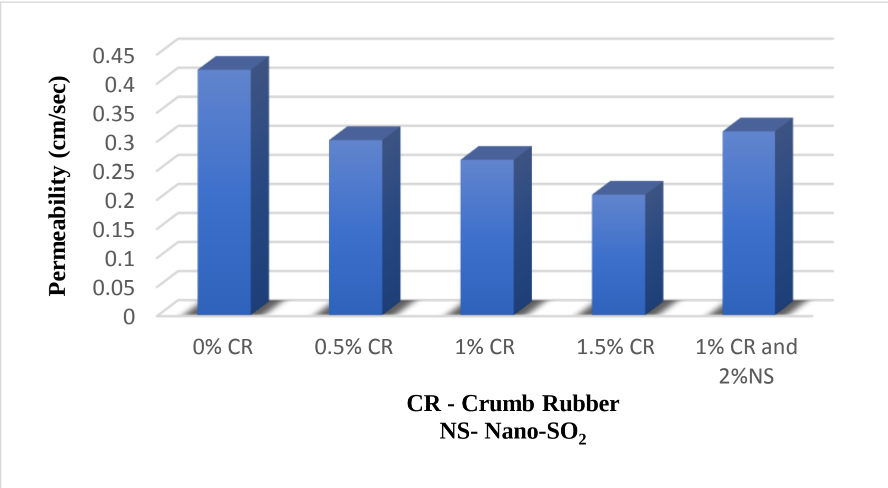


Figure 5.15 Comparison of permeability of in different combination of additives

The permeability value for various porous bituminous mixture with variation of Crumb Rubber and Nano Silica content are tabulated below.

Table 5.9 Variation of permeability for different combination of additives, at their respected OBC% value.

% CR content at OBC	0	0.5	1	1.5	1
% NS content at OBC	0	0	0	0	2
Permeability(cm/sec)	0.425	0.302	0.268	0.209	0.315

5.3.5 Indirect Tensile Strength (ITS)

The static method is used to measure the indirect tensile strength (ITS) of bitumen mixtures, which aids in determining how resistant a certain mix is to moisture susceptibility. At their OBC, mixes with varying crumb rubber and nano silica contents underwent static indirect tensile tests.

Dry-Wet ITS

For mixes with various types of additives at their OBC, dry ITS, wet ITS, and tensile strength ratio are calculated using an equation. Below is a graphical illustration of it.

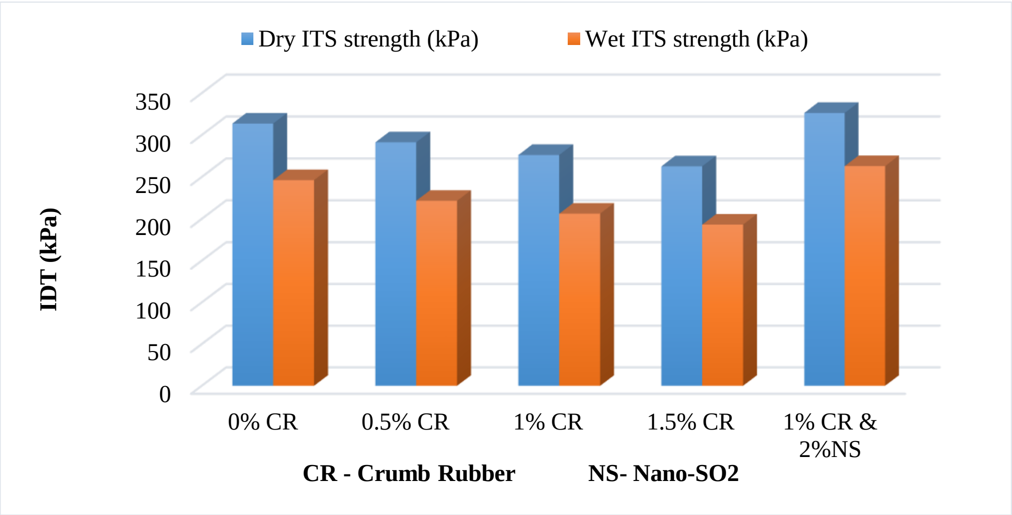


Figure 5.16 Comparison of dry and wet IDT for different mix at their respected OBC

The tensile strength value in both the dry and wet ITS is dropping, as can be seen in the above figure, as rubber content increases. However, the ITS values in both Dry and Wet have increased dramatically once NS was added to the mixture. With the increase in Crumb Rubber and Nano Silica give better value than other mixes (V. Khilari, 2017).

Table 5.10 Result summery of dry and wet IDT

% CR content	% NS content	Dry ITS strength (kPa)	Wet ITS strength (kPa)	TSR %
0	0	313.73	246.22	78.45
0.5	0	291.34	221.66	76.09
1.0	0	276.25	206.27	74.69
1.5	0	262.70	193.19	83.58
1.0	2	326.34	262.96	80.53

Freeze-Thaw ITS

In the given figure a comparison between dry and Freeze-Thaw ITS values are shown, the ratio of Freeze-Thaw ITS and Dry ITS is also represent as ITR2.

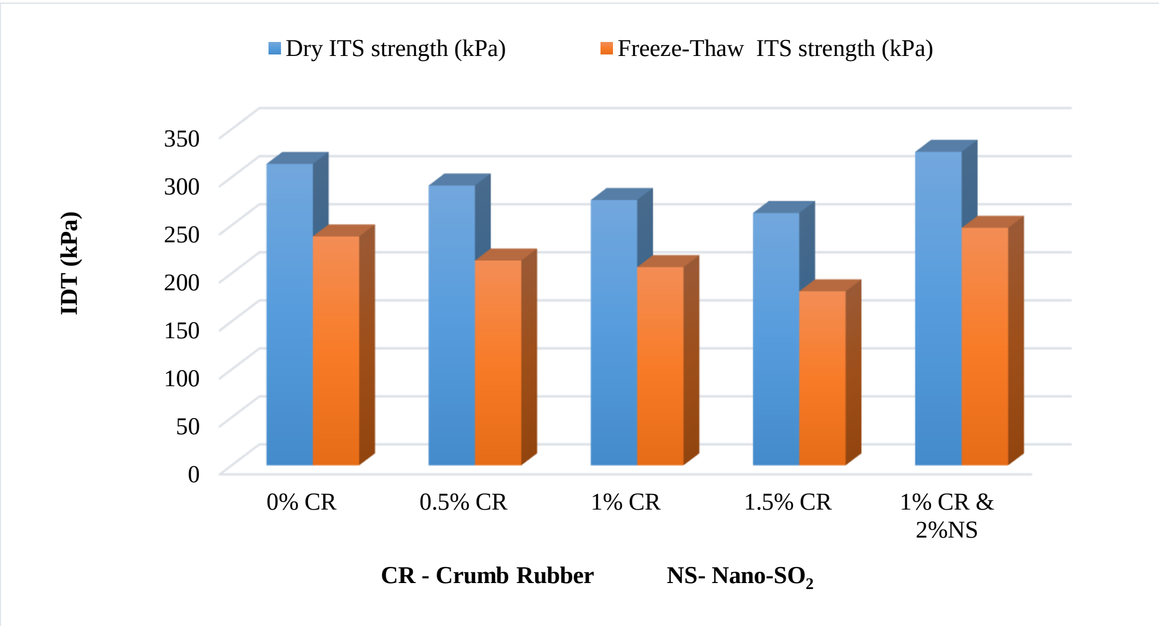


Figure 5.17 Comparison of dry and Freeze-Thaw IDT for different mix at their respected OBC.

In every instance, the quantity of CR declined as freeze-thaw ITS increased, while the value of ITS for the combination of CR and NS improved. Additionally, the TSR2 value grew in the previous instance as well.

Table 5.11 Result summery of dry and freeze-thaw IDT

% CR content	% NS content	Dry ITS strength (kPa)	Freeze-Thaw ITS strength (kPa)	TSR %
0	0	313.73	238.39	75.99
0.5	0	291.36	213.23	73.25
1.0	0	276.21	206.36	74.58
1.5	0	262.65	181.28	68.95
1.0	2	326.34	247.33	75.77

5.4 Findings of the study

Based on the test results of OGFC bituminous concrete and OGFC bituminous concrete modified with CR, the following conclusion are drawn:

- The findings of the stone aggregate test indicate that the experiment's aggregate is of standard quality.
- Marshall test results show that adding the CR to the bituminous mix has certainly improved the test results. The stability values obtained from RPA mixes are certainly higher than those obtained from unmodified bituminous mixes.
- It is also obvious that the flow value and the percentage of air void were both decreased by the larger percentage of crumb rubber.
- Moreover, the OBC% has also decreased along with the increase in CR%. In the case of an unmodified bituminous mix, the OBC% obtained is 6% after adding CR in the dry process; it reduces to 5.65% for 0.5% CR content and all the way down to 4.5% for 1.5% bitumen contentment.
- The permeability of the porous bituminous concrete increases with the incorporation of nano silica into the bituminous mixture. Since nano silica was added, the created mixture has more air voids than virgin bitumen mix, which helps improve the permeability.

- The increase in CR content in the OGFC mix has decreased the Indirect Tensile strength of concrete. However, the 2% nano silica added to the binder greatly increased the concrete's tensile strength.

CHAPTER- 6

EXAMINING THE STRUCTURAL BEHAVIOUR OF A POROUS ASPHALT MIXTURE WITH STEEL SLAG USED AS PARTIAL REPLACEMENT OF THE STONE AGGREGATES

6.1 General

This study focuses on the structural behavior of a porous asphalt mixture in which some of the stone aggregates have been substituted by steel slag. The study's goal was to look into the impact of using steel slag in place of some of the stone aggregate on the mix's structural and mechanical properties as permeable asphalt. A laboratory mix method of design was used for the investigation, with various proportions of steel slag being used in place of some of the stone aggregate. Several tests, including the Marshall Stability test, the Permeability test, and the Cantabro abrasion test, were used to assess the outcome of porous asphalt mixes. The results showed that using steel slag in place of some of the stone aggregate improved the physical and structural properties of the permeable asphalt mix. Stability and durability were best in the mixture where steel slag replaced 20% and 40% of the stone aggregate, respectively. The study also examined how the various concentrations of steel slag affected the porous nature of the permeable asphalt mixture. The results demonstrated that the porosity decreased as the amount of steel slag increased, which may have an effect on the mix's permeability. For porous asphalt combinations, a reduction in porosity was discovered to be within acceptable bounds. The study results imply that using steel slag in porous asphalt mixes as a partial substitution for stone aggregate can enhance the mix's structural and mechanical qualities while lessening the construction industry's environmental impact. To attain the greatest outcomes, further study is advised to examine the mix's long-term performance and optimize the ratio of steel slag replacements in the mix.

6.1.1 Introduction

The highway network is recognized as the basis of the country's economy since it links travelers to other modes of transportation, industrial zones, retail districts, institutional places, and nearly every kind of land use area. Certainly, an enormous quantity of material is required to build such a network. Local aggregate in the form of rocks, gravel, and sand has been used in construction for thousands of years. The construction of the Roman Empire's road system and aqueducts necessitated a sizable aggregate change. Aggregate use significantly increased as a result of the invention of concrete. Key ingredient aggregate serves as a reinforcement and increases the overall strength of the composite when combined with a binder. Academics have shifted their attention away from possibilities for the creation of sustainable and green pavements due to economic, environmental, technical, and technical reasons and a lack of suitable building materials. They have therefore investigated a number of recyclable substances that may be employed as aggregates, particularly steel slag.

The quick growth in traffic volume and heavy loads, along with environmental factors, reduce the pavement's useful life. Due to the rise in accidents each day, these damages, such as rutting and inadequate skid resistance from aggregate polishing, lead to fatal wrecks. The majority of the mechanical and physical characteristics of natural aggregate are also present in steel slag, if not better. As a result, it is used as a building component across the world, especially in the construction of highways. Steel slag is sufficiently strong, thick, and abrasion-resistant due to its porous, extremely rough-textured, angular composition, and high iron content. These qualities may reduce early deterioration and enhance the structural and functional efficiency of the pavements by increasing the safety of road users. An increasing problem is the lack of raw materials for construction projects on a global scale. This has led to an increase in research on resource conservation and using ecologically friendly methods. In Porous asphalt pavement mixtures, steel slag can be used to partially substitute natural aggregate. These traits could reduce early deterioration and enhance the structural and operational efficiency of the pavements by increasing the safety of all users of the roads. The issue of a global lack of natural resources for building projects is getting worse. As a result, the use of environmentally friendly supplies and material conservation have emerged as active study fields. To substitute some of the natural aggregate in mixtures for porous asphalt pavements, steel slag may be used.

A new kind of asphalt Mixture was created as a result of advances in hot-mix asphalt pavement technology. In several locations, porous asphalt (PA) is applied as a surface for paving. A form of asphalt surface known as porous asphalt allows water to travel through it, lowering the risk of floods and enhancing stormwater drainage. A particular combination of aggregates, binders, and other additions that enable the pavement to be permeable is used to create porous asphalt. Sand, gravel, and crushed stone are the aggregates that are used in porous asphalt. Porous pavement is a form of paved surface that enables water to permeate through and into the subsurface because it has a higher-than-average percentage of air spaces. By replacing conventional pavement with this porous surface, drainage from parking lots and roads may soak through the soil and be cleaned for water quality. In all permeable pavement systems, a strong, load-bearing prior covering covers a stone bed that gathers rainfall before it percolates into the underlying soil.

Natural Stone Aggregate | Steel slag Aggregate | Crumb rubber

Figure 6.1 Aggregates and additive used in the study

6.1.2 Importance of the study

By utilizing these waste resources, the problems of waste disposal and aggregate scarcity are addressed. Investigating the effects of coarse naturally occurring stone aggregates and the characteristics of asphalt concrete made with different amounts of coarse steel slag aggregates with 1% crumb rubber (CR) is the goal of the current study.

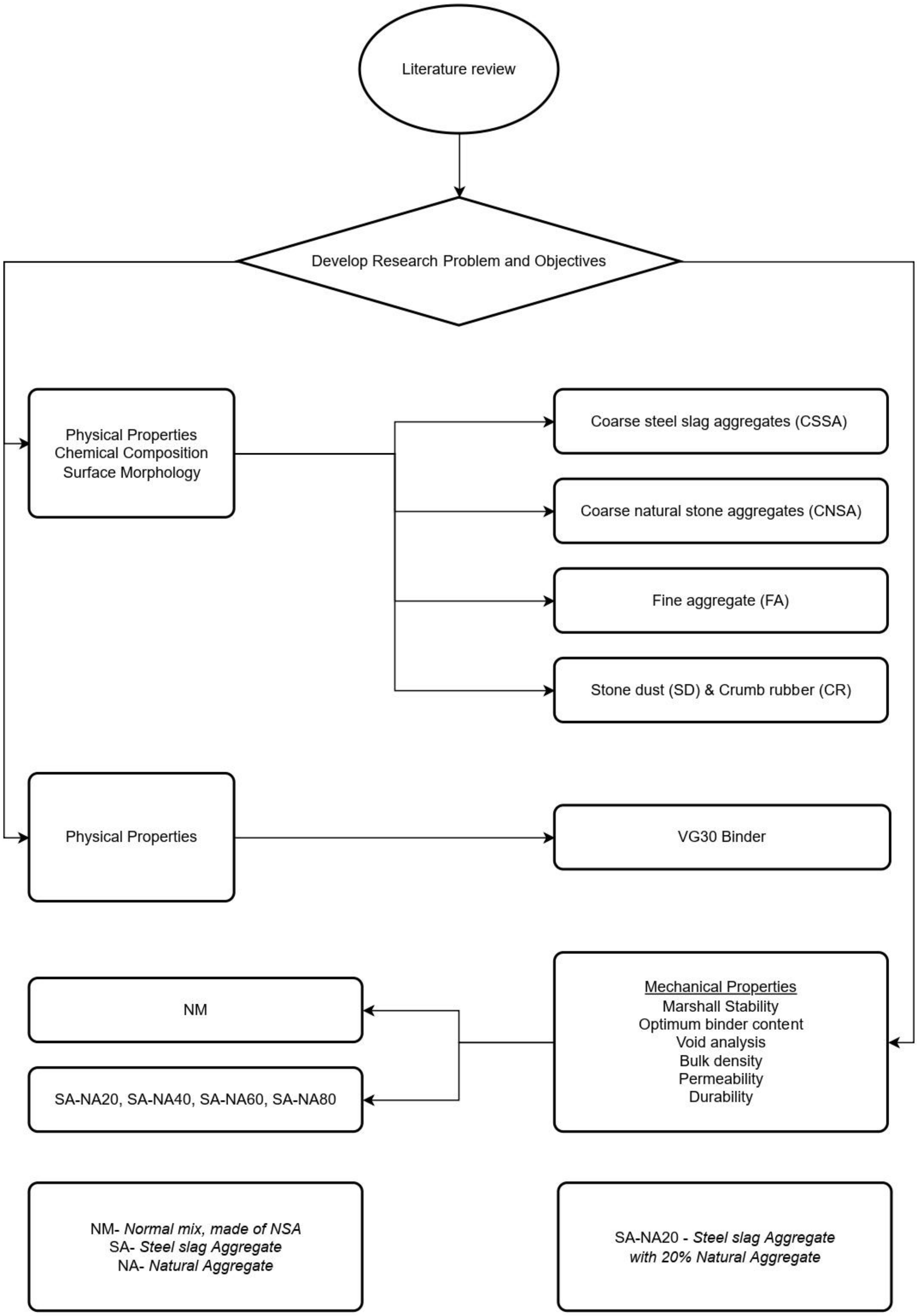


Figure 6.2 Flowchart of the Experiment

6.1.3 Objective of Present Study

To meet the goals of sustainable growth, which benefits both our economy and the environment, we must modernize our technologies. It is necessary to list the precise goals of the current study before moving on to find an appropriate, economically viable, and environmentally friendly solution. In this study, the structural behavior of porous asphalt mixtures is investigated using steel slag as a temporary replacement for stone aggregate. In relation to various steel slag percentages, the effectiveness of porous asphalt blends will be investigated. Utilizing laboratory testing techniques, the structural behavior of the asphalt mixtures is going to be assessed.

The following describes the study's goal:

- To determine the stability of porous asphalt mix by using steel slag.
- To test the porous asphalt and steel slag mixture's permeability properties.
- To determine whether the porous asphalt course with steel slag will last long enough.

6.1.4 Experimental program

The qualities of asphalt concrete constructed using CSSA, which substitutes coarse steel slag aggregates for coarse natural stone aggregates, are examined in this study. In a complete physical experiment, two stages may be distinguished. Bitumen and aggregate physical properties are evaluated in the initial phase using simple test methods. Additionally, aggregates' chemical makeup is examined. In the subsequent stage, various asphalt blends are added to the mixture, including the standard mix (made up of 100% naturally occurring stone aggregate), the steel slag mixture (which partially replaces CNSA with CSSA), and crumb rubber supplements (i.e., 1%). Therefore, these mixtures' labels are NM, SA-NA20, SA-NA40, SA-NA60, and SA-NA80. All of these combinations are assessed using the Marshall Mix Method, the Permeability Test, and the Cantabro Test.

6.2 Materials and Methodology

6.2.1 Materials

6.2.1.1 Aggregates

Figure 6.1 displays the additives and aggregates used in the study. Natural stone aggregates and steel slag aggregates are the two types of aggregate used in the manufacture of asphalt concrete. India's Tripura Ispat Company provides the SSA. In this work, the coarse natural stone aggregates were partially substituted by coarse steel slag aggregates. At 20%, 40%, 60%, and 80% of the aggregate's total weight, the SSA is used in place of the NSA. There were substitutes for both coarse and fine aggregate grains. A list of the characteristics of coarse aggregates can be found in Table 6.1. The SSA is more abrasion-resistant and resistant to impact than the NSA. It indicates that these stones are sufficiently powerful to bear the weight that automobiles throw at them. Additionally, the SSA has a lesser flakiness and elongation index than the NSA since it is significantly more angular. Because iron compounds are present in SSA, it has a higher specific gravity than NSA. The SSA is better than the NSA at absorbing water. However, both aggregates meet the minimum requirements of the MoRTH guidelines. Porous asphalt concrete is created using bituminous concrete in open gradation, as seen in Fig. 6.3. The log-scale graph displays the desired gradation.

Table 6.1 Coarse aggregates' physical properties.

Properties	SSA	NSA	Limits	Code
Impact value, %	14.25	15.51	Max 24	IS: 2386-part IV (BIS,2007b)
Crushing value,%	14.98	15.71	-	IS: 2386-part IV
Abrasion value, %	16.32	19.69	Max 30	IS: 2386-part IV (BIS,2007b)
Specific gravity	3.09	2.72	-	ASTM C 127 (ASTM 2015a)
Water absorption, %	1.75	1.372	Max 2	ASTM C 127 (ASTM 2015a)
Flaky and elongation index, %	12.87	22.96	Max 35	IS2386-part I (BIS,2007a)

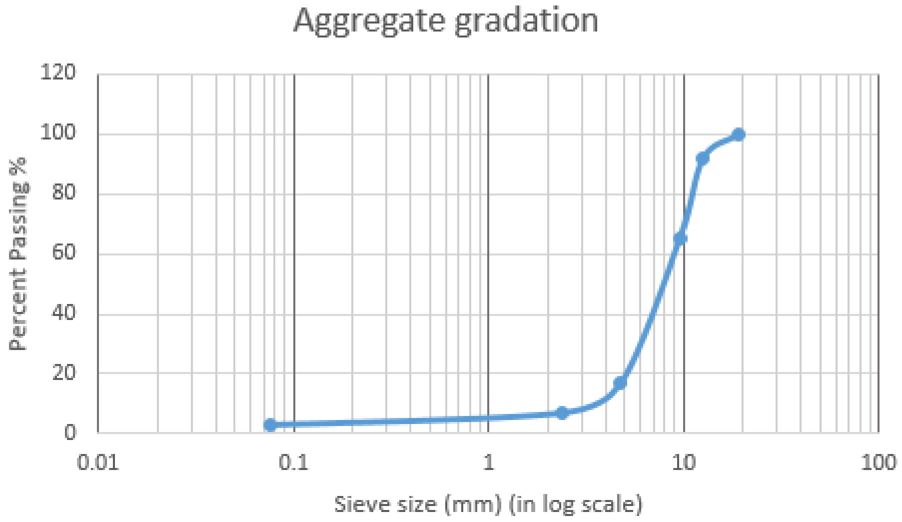


Figure 6.3 Open gradation chart

The mineral composition of NSA and SSA is investigated by energy-dispersive X-ray spectroscopy (EDX) (D. Paul et.al. 2021). A lot of the NSA and SSA are composed of components made of silica (Si) and aluminum (Al). Because such stones are formed from steel industry waste, SSA contains additional elements like iron (Fe) and manganese (Mn). Table 6.2 contains a list of the mineral makeup of the materials used in this work. Due to the substantial amount of Fe_2O_3 present, the SSA is tougher, harder, and denser. Additionally, it contains a negligible 1.12 ppm of MgO, which results in less significant volumetric modifications to road treatments.

Table 6.2 Mineral composition of different materials. (D. Paul et.al. 2021)

Constituent	SSA,%	NSA,%
SiO_2	18.47	59.55
MgO	1.12	2.77
Fe_2O_3	43.49	1.30
CaO	15.33	12.31
Na_2O	-	3.01
SO_3	-	0.51
Al_2O_3	7.21	19.01
K_2O	-	2.27
MnO	11.90	-

6.2.1.2 Fine aggregate, Filler, and additives

Employing natural fine aggregate, filler elements such as stone dust, and additives like crumb rubber (CR), bituminous mixes are created in this work. Table 6.3 offers a list of the specific gravities of fine aggregate, filler, and additives. The crumb rubber is included at a lower level, i.e., 1% of the total amount of aggregate.

Table 6.3 Characteristics of Fine aggregate, Filler, and additives

Properties	Specific gravity
Fine aggregate	2.75
Stone dust	2.761
Crumb rubber	1.143

6.2.1.3 Bitumen

The bituminous binder VG30, which is extensively utilised on Indian pavements, was chosen for this study. Table 4 includes a list of the VG30 binder's features. It is clear that VG30 binders adhere to the regulations' rigorous requirements.

Table 6.4 Characteristics of VG30 binder.

Properties	Values	Limits	Method
Penetration value (25 °C)	63	Min 45	IS: 1203
Penetration Index (PI)	-0.732	-	-
The softening point, °C	53	Min 47	IS: 1205
Ductility (25 °C), cm	>100	Min 75	IS: 1208
Specific gravity	1.02	Min 0.99	IS: 1202
Weight loss (RTFO), %	0.73	Max 1	ASTM D2872
Viscosity (60 °C), pose	2976	2400-3600	ASTM D4402

6.2.2 Methodology

6.2.2.1 Marshall Mix method

For combinations of the normal mix (NM) and steel slag asphalt (SSA), the Marshall Mix method is employed for determining the optimal binder content. By adjusting the binder content by 0.5%

at a time, Marshall Samples are made in every potential combination. SSA compositions generated with 80, 60, 40, and 20% of the aggregate weight must be evaluated against each other, and modifiers with 1% must be added to all SSA mixtures. The mean results for three cylindrical Marshall Samples with a 10.17 cm diameter and a 6.35 cm thickness, respectively, were tested at various binder contents. Finished cylindrical samples were kept for a water bath treatment at 60 °C for around 40 minutes. The samples were then loaded until they collapsed at a predefined loading rate of 2 inches per minute. Marshall Stability of each sample was measured as the strength at collapse. The minimal standards of NAPA IS 131 and UNHSC are reviewed at OBC together with Marshall specifications, including stability, flow, air voids, voids filled with the binder (VFB), voids in mineral aggregate (VMA), and unit weight (UW).

6.2.2.2 Permeability Test

The constant head permeability method is adopted to determine the marshal sample's permeability. A tripod stand, a marshal collar, a water collecting container, and a volume measurement device make up the setup for this technique. Marshall Water flows into the sample with mould from a water tap at a constant height from the side with the most mould inserted into it. The sample is fastened to the collar. The volume of water is then estimated as the sample percolates over a period of time. With the aid of IS: 3085-1965, the permeability coefficient is determined from Darcy Law.

$$K = \frac{Q}{AT\frac{H}{L}} \qquad (1)$$

Where K = Permeability coefficient in cm/sec; Q = Amount of water percolating throughout the test in milliliters once a steady state has been established; A = The sample face area in cm^2, T = duration in seconds over which Q is measured; $\frac{H}{L}$ = the ratio of the specimen thickness to the pressure head, both represented in the same units.

6.2.2.3 Cantabro abrasion test

The Cantabro abrasion test method is adopted to determine whether the compressed porous asphalt course (PAC) specimen has a sufficient level of durability. Most agencies today recommend applying this test to PACs with a mixed design, either as a requirement or as an option. To evaluate the mixture's unaged abrasion loss, a compacted sample of the PAC mix was placed in a Los Angeles abrasion drum with no abrasive charges. At a speed of 30 to 33 rpm, the machine was then spun for 300 revolutions. The ideal working temperature is 25 °C. The specimen's starting weight is measured first (A), and then its ultimate weight (B) is determined after 300 rotations. When comparing the weight of fragmented particles, one can measure abrasion loss compared to the original weight of the specimen.

$$Percentage\ Loss = (\frac{A-B}{A}) \times 100 \qquad (2)$$

6.3 Results and discussions

6.3.1 Marshall Mix method

The optimal binder content of the asphalt mixture is calculated using the Marshall Mix method. Table 6.5 displays the results of the mix layout for both the conventional Normal Mix (NM) and the SSA mix with various bitumen contents. The Marshall parameters are mentioned there.

Figure 6.4 Marshall Test samples

Table 6.5 Results of a Marshall Mix design.

Type of Mix	Marshall components						
	OBC%	Stability, kN	Flow, mm	Va, %	VMA, %	VFB, %	UW, (g/cc)
NM	5.10	8.43	2.778	18.768	26.122	28.56	1.919
SA-NA20	4.95	9.118	2.933	18.404	27.788	27.982	2.223
SA-NA40	4.96	9.742	3.420	18.419	28.482	25.881	2.228
SA-NA60	5.03	9.553	3.018	18.604	26.305	27.883	2.211
SA-NA80	5.06	9.005	3.15	18.575	25.088	27.665	2.11

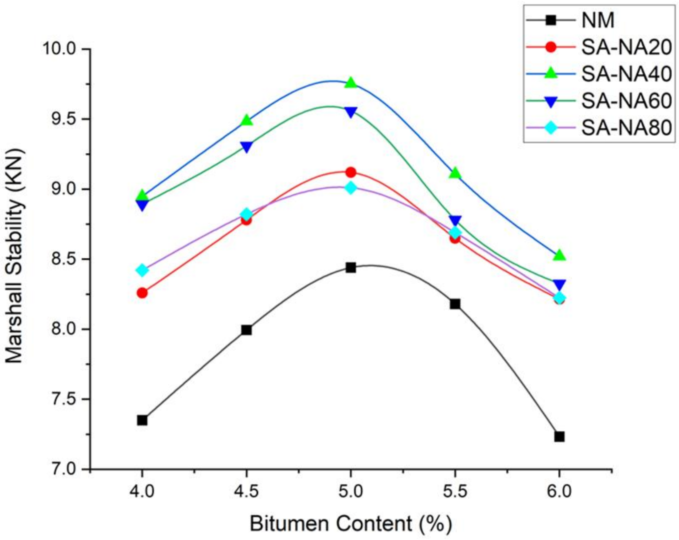


Figure 6.5 Stability curves for different mixtures

When the results of mixed design are compared, it becomes clear that steel slag aggregate and natural stone aggregate have excellent qualities, high stability values, and durability against permanent deformation. The specimens made with SA-NA40 demonstrated the greatest stability when compared to specimens made with natural aggregates, as shown in Fig. 6.5. As a result, the SSA has lower values for crushing and Los Angeles abrasion as compared with natural aggregates.

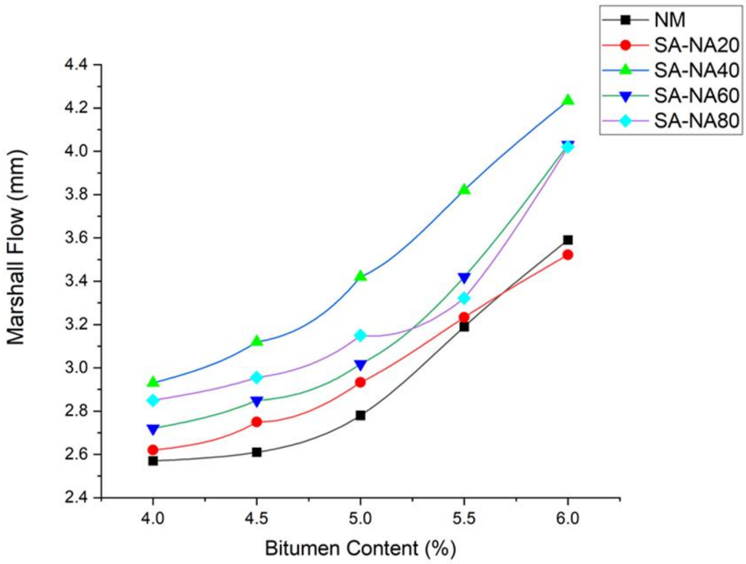


Figure 6.6 Flow curves for various bitumen contents and mixes

The vertical displacement of the asphalt specimen while performing the Marshall stability is known as Marshall Flow, and it is monitored from the commencement of loading until the stability starts to drop. The high value of flow, which also predicts eventual rutting-related pavement degradation, illustrates the mix's significant flexibility. Additionally, a low flow value can result from a high void content and a deficiency in binder, which could hasten the premature breakdown of the pavement. In order to measure the flow test, ASTM D1559 was followed. Fig. 6.6 displays the flow numbers for various SSA percentages at varying binder levels. The test findings show that flow values grow as the SSA value rises. The optimal values for flow for medium traffic loads are from two to four mm, according to the AI standards for making Porous Asphalt Concrete (PAC) mixtures. The greatest flow value was 4.233 mm in an asphalt mixture with 60% SSA and 6% binder content, and the lowest flow value was 2.57 mm in mixtures formed entirely of virgin aggregate and 4% binder, per the test findings. Because of this, the specimens with 60, 40, and 20% SSA and 6% bitumen concentration did not fit the criteria.

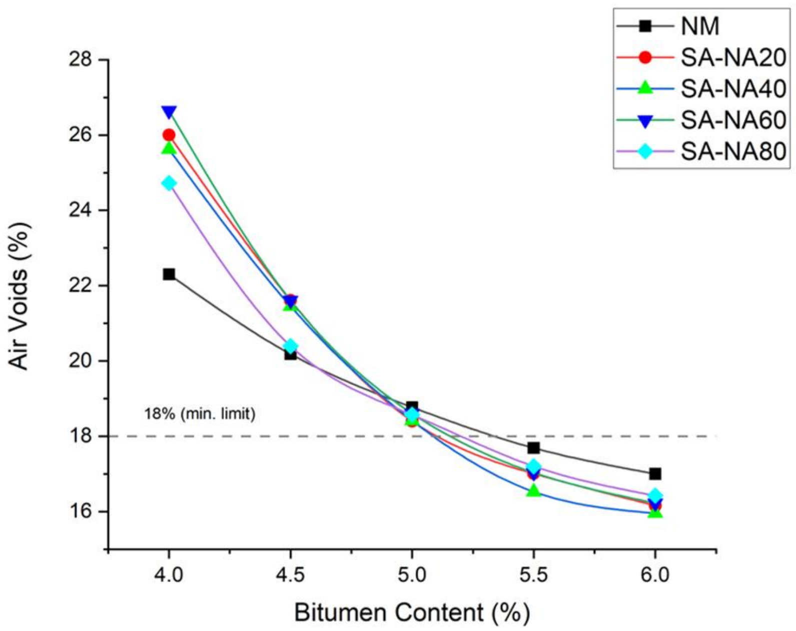


Figure 6.7 Air Voids curves for various bitumen contents and mixes

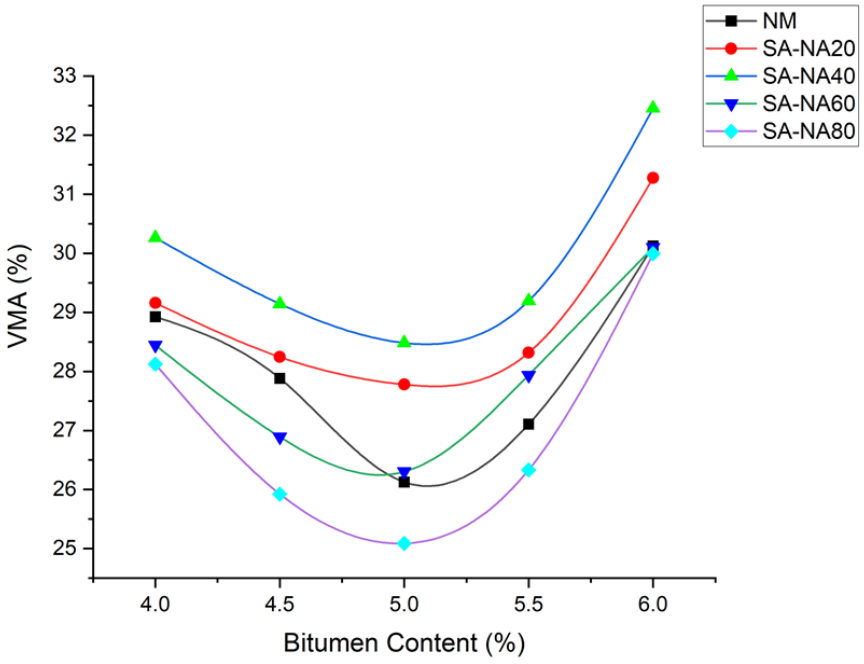


Figure 6.8 Voids in mineral aggregate curves for various bitumen contents and mixes

When making permeable pavement, a particular aggregate mix with a high proportion of empty spaces is used to create the air voids. Water can therefore leak into the earth below by penetrating the pavement and entering the crevices. In order to minimize cracking and other sorts of pavement degradation, the air gaps also give the asphalt room to grow or shrink in response to temperature variations. Depending on the precise mix design and intended level of permeability, the quantity of air voids in porous asphalt pavement can change. In PCA, the minimal air voids typically make up 18 to 25 percent of the entire asphalt mixture volume. NAPA IS 131 and UNHSC both concur. Figures 6.7 and 6.8 demonstrate that in specimens treated with SSA, the air void percentage (AV) decreased but the voids in mineral aggregate percentage (VMA) increased in comparison to the values of the NM specimens.

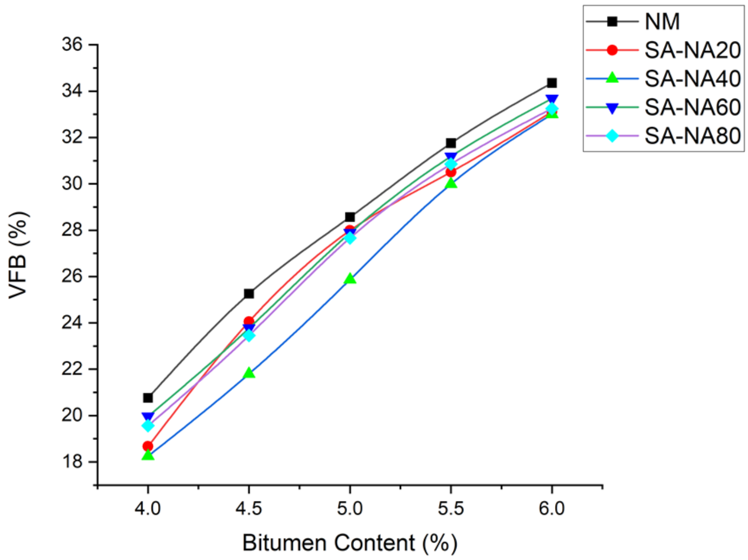


Figure 6.9 Voids filled with bitumen curves for various bitumen contents and mixes

In porous asphalt pavement, bitumen-filled voids are not totally impervious. The bitumen, on the other hand, provides a level of water infiltration resistance that allows water to pass through the pavement and soak into the subsurface soil at a controlled rate. By doing so, the quantity of storm water runoff is decreased and the general health of our surroundings is improved. In permeable asphalt pavement, the utilisation of bitumen-filled gaps is a crucial part of the design and construction process. Permeable asphalt pavement is able to efficiently control stormwater runoff while retaining its underlying strength and durability over time by using an arrangement of air gaps and voids filled with bitumen. VFB will consequently rise when bitumen content does.

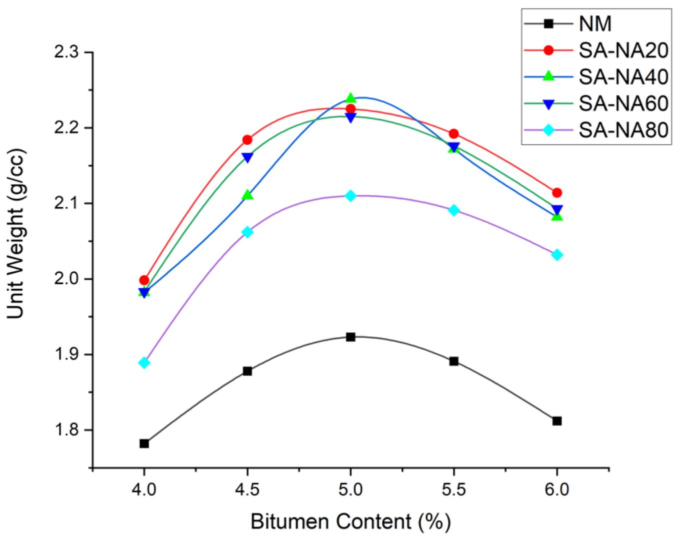


Figure 6.10 Unit Weight with bitumen curves for various bitumen contents and mixes

The findings show that applying various SSA fractions to the asphalt mixture somewhat enhances its bulk density. The bulk density of the asphalt mixture rises as the bitumen content does, as seen in Figure 6.10. This is mostly caused by the iron compounds found in SSA.

The Optimal Bitumen Content (OBC) decreased from a value of 5.12% for samples created with natural aggregate to 4.98, 4.99, 5.02, and 5.05% for specimens made with 80, 60, 40, and 20% SSA, respectively, in terms of the results of the Marshall tests performed on the prepared samples. Thus, the volume characteristics VMA, VA, and VFB fulfill the essential requirements as per NAPA IS 131 and UNHSC regulations. Use of steel slag in porous mix gives improvement in the result in terms of different parameters (D. Paul, 2021).

6.3.2 Permeability Test

Using the constant head test method, the permeability of each combination was assessed; the results are shown in Figure 6.12. When crumb rubber was added, the mixture's permeability tended to decrease. The results, which were statistically comparable, showed that the mixtures with a high binder component of NM had the lowest permeability values. There were variations in permeability even though the remaining four combinations (SA-NA20, SA-NA40, SA-NA60, and SA-NA80) had binder levels that increased by 0.5%.

Figure 6.11 Permeability Testing Samples

The permeability of the permeable asphalt mixtures decreased after the incorporation of CR, and it will continue to decline if more rubber content is added. This was also most likely caused by the inclusion of crumb rubber, which increased viscosity and increased the amount of ideal binder. The binder film layer grows along with the binder content, causing the pores in the mixture to become smaller and their flow channels to become more constrained.

Table 6.6 Permeability Test Results (*Constant Head Method*)

Bitumen Content (%)	Permeability (cm/sec)				
	NM	SA-NA20	SA-NA40	SA-NA60	SA-NA80
4	1.24685	1.25140	1.30410	1.29870	1.24922
4.5	0.90014	0.91014	0.98282	0.96451	0.90121
5	0.64171	0.74201	0.87891	0.87254	0.68974
5.5	0.29881	0.33280	0.51220	0.49925	0.37872
6	0.09218	0.10951	0.10998	0.10912	0.09985

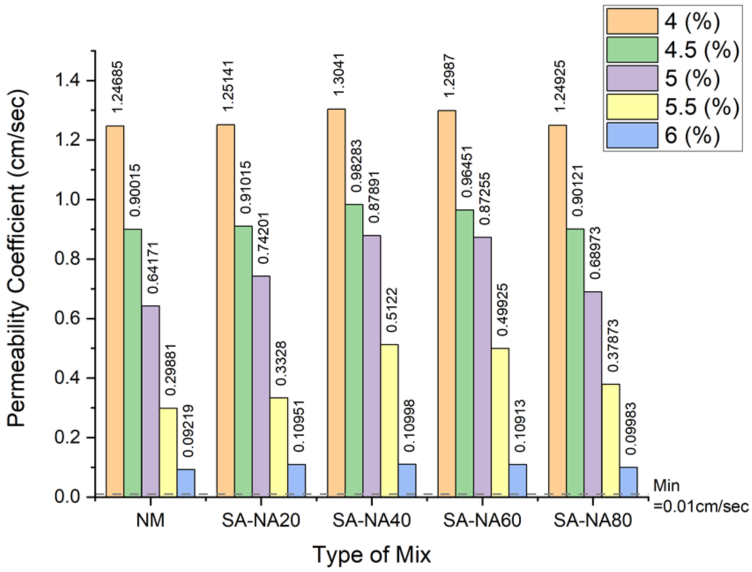


Figure 6.12 Relationship between the Value of the Coefficient of Permeability and Type of Mix

Table 6.6 displays a summary of the permeability test results. The connection among the amount of the permeability coefficient and bitumen content is depicted in Figure 6.12. As shown in Fig. 6.12, the permeability coefficient is dropping. At 4%, 4.5%, 5%, 5.5%, and 6% bitumen concentration for NM, SA-NA20, SA-NA40, SA-NA60, and SA-NA80.

6.3.3 Cantabro abrasion test

Using the Cantabro abrasion test, the capacity of the porous asphalt mixtures to resist ravelling was evaluated. For unaged samples and aged specimens, it is advised that the abrasion loss during this test should not exceed 20% and 30%, respectively. UNHSC and NAPA IS 131 are in agreement.

The samples used in this experiment were aged in a 60 °C oven for seven days prior to testing. The outcomes are displayed in Figure 6.13.

As seen in Figure 6.13, increasing the asphalt ratio lowers the abrasion ratio while also potentially increasing the bonding of the aggregate particles. The bonding is enhanced, the strength is increased, and the surface area is increased by adding the various SSA percentages (80, 60, 40, and 20) and 1% of crumb rubber to the mixture, which reduces the abrasion loss.

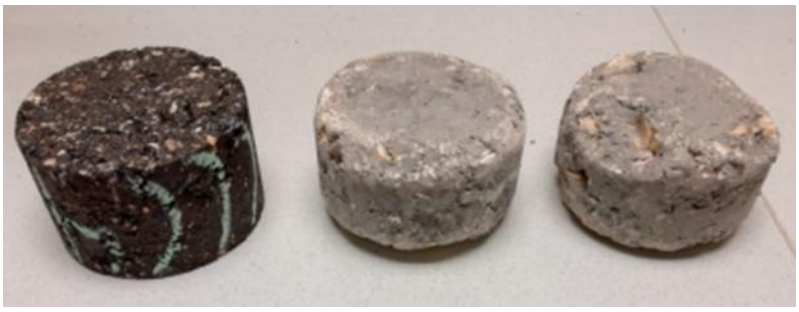


Figure 6.13 Cantabro Abrasion Unaged & aged samples

Table 6.7 Cantabro abrasion Test (Unaged) Results

Bitumen Content (%)	Unaged Abrasion Loss Result				
	NM	SA-NA20	SA-NA40	SA-NA60	SA-NA80
4	40.03932	37.93423	38.51215	39.0901	39.9594
4.5	31.90351	28.75217	29.08047	29.9221	30.8262
5	24.89273	19.06536	19.10875	19.3243	21.2323
5.5	19.68045	18.55124	18.79197	18.9211	19.1986
6	18.83126	18.02179	18.21243	18.3725	18.6161

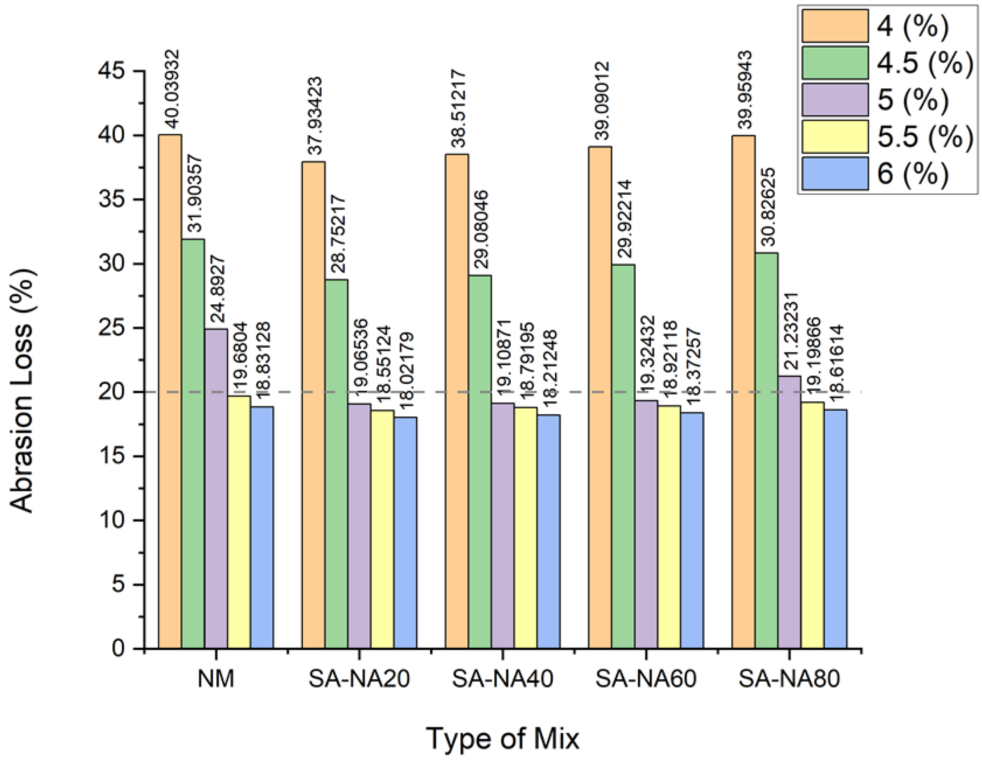


Figure 6.14 Relationship Between the percentage of Abrasion loss and Type of mix (Unaged)

Findings from unaged abrasion loss tests on mixtures of asphalt with various bitumen contents are shown in Table 6.7. It displays the bitumen content percentages and related abrasion loss values for each asphalt mixture made with various aggregate types, including NM, SA-NA20, SA-NA40, SA-NA60, and SA-NA80. The table shows that the abrasion loss falls for all types of aggregates as the bitumen content rises. This suggests that a larger bitumen percentage enhances the asphalt mixtures' resilience to abrasion.

The table also indicates that the various aggregate types have variable effects on the asphalt mixtures' ability to resist abrasion. For instance, among all bitumen content levels, the SA-NA20 aggregate type has the lowest abrasion loss values, whereas the NM aggregate type has the highest abrasion loss values. According to the required bitumen content and aggregate type for the purpose, the information in this table can be utilized to help choose asphalt mixtures with suitable abrasion resistance capabilities.

Table 6.8 Cantabro Abrasion Test (Aged) Result

Bitumen Content (%)	Aged Abrasion Loss Result				
	NM	**SA-NA20**	**SA-NA40**	**SA-NA60**	**SA-NA80**
4	45.85512	43.84486	44.14134	44.54073	45.06424
4.5	40.98084	36.30849	37.22370	38.47865	40.02993
5	37.43819	29.98645	30.00506	30.06757	34.38806
5.5	29.35242	27.03180	27.43289	27.93921	28.88145
6	26.74891	24.39229	24.95784	25.45206	26.27676

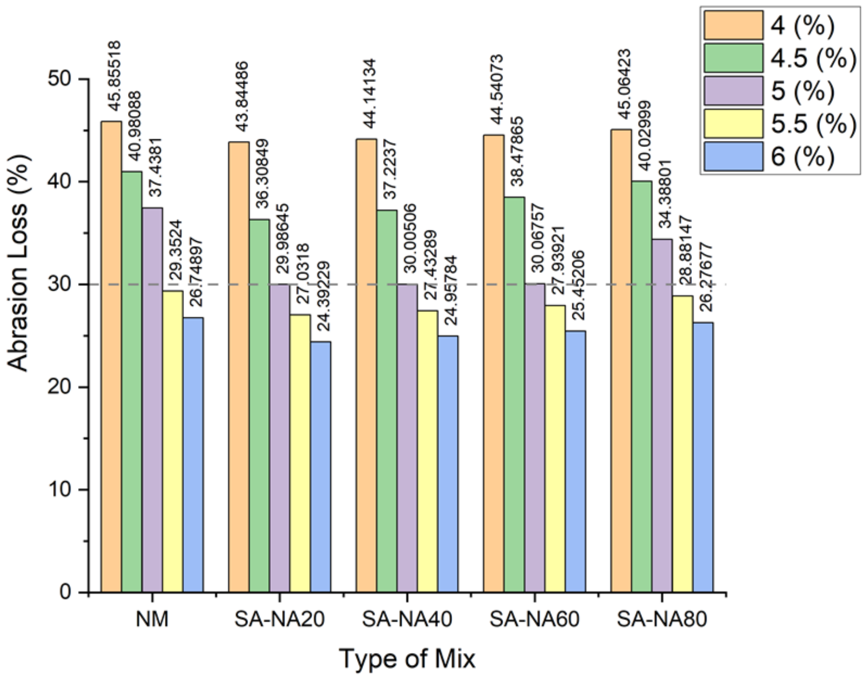


Figure 6.15 Relationship Between the percentage of Abrasion loss and Type of mix (Aged)

According to Table 6.8, the aged abrasion loss for all aggregate types generally reduces as the bitumen concentration rises. This shows that even after aging, asphalt mixtures with a higher bitumen component may be more resistant to abrasion. The abrasion durability of asphalt mixtures over time is also shown to vary according to the various aggregate types. For instance, across all bitumen content levels, the SA-NA20 aggregate type has the lowest old abrasion loss values, but the NM aggregate type has the greatest old abrasion loss values.

When choosing asphalt mixtures for applications that demand great durability and resilience to long-term wear and tear, the findings of the aged abrasion loss tests can be helpful. Based on the necessary bitumen content and aggregate type, one can select the asphalt mixture that best suits their unique demands by using the information from these tables.

6.4 Findings of the study

In comparison to conventional coarse natural stone aggregate (CNSA) pavement, coarse steel slag aggregate (CSSA) exhibits better stability and strength and much higher permeability. The goal of the study is to investigate the effects of replacing steel slag in regions with moderate traffic with open grade.

In this investigation, SSA, a steel industry waste product, was substituted for natural aggregate in a number of asphalt concrete compositions. The enhancement of the studied samples' mechanical and physical properties was utilized to gauge how well SSA substituted natural aggregate. The study's findings are as follows:

- Unlike conventional pavements, porous asphalt pavements are often built over an uncompacted sub-grade to maximize infiltration into the soil.
- When compared to regions with standard pavement, paved areas constructed using earlier paving technologies produce less stormwater runoff. The primary way to reduce stormwater runoff is to increase the quantity of precipitation that seeps into the ground, which is what typical paving would do.
- When porous asphalt is appropriately built, water can quickly percolate through the porous pavement because it has larger air voids and more open space among the interlocking aggregate skeletons.
- Coarse steel slag aggregates offer superior physical properties compared to coarse natural rock aggregates. However, with regard to water absorption, Coarse steel slag aggregates surpass coarse natural rock aggregates. However, no aggregate exceeds the 2% maximum limit for water absorption.
- The Marshall Specification for the Design of Porous Asphalt Concrete is mostly satisfied by the physical features of SSA. According to the results of laboratory studies, SSA seems to be particularly useful for use in India to reduce its dependency on naturally occurring aggregate.
- As bitumen content rises, the coefficient of permeability's value decreases.

- For SA-NA20, SA-NA40, and SA-NA60, samples created with 5.0% bitumen could obtain the limit value (both 20% and 30%), whereas samples made with 5.5% bitumen might reach the maximum value for NM and SA-NA80. It was shown that the elimination of Cantabro particles was greatly improved by the addition of CR.
- It is believed that using natural aggregate in the HMA layer of road pavement is a waste of a finite natural resource. It is acknowledged that the utilization of wasted (secondary) materials benefits both the environment and society. When creating aggregate for concrete and asphalt mixtures, steel slag can be used as a suitable replacement for other waste materials.

CHAPTER- 7

ENGINEERING PROPERTIES OF PERVIOUS CONCRETE WITH GGBS AS A PARTIAL REPLACEMENT FOR CEMENT

7.1 General

Porous Concrete has been developed as an emerging technology since it is environmentally and hydrologically sustainable. The use of porous concrete is limited to parking lots, walkways, footpaths, etc. But using porous concrete on the road for vehicular movement is a challenge for any researcher. The current approach is to use porous concrete on the low-volume road by improving its engineering properties. Using a variety of design criteria, this study prepares a number of test samples before examining the characteristics, like strength and permeability, of porous concrete mixes. Regarding characteristics such as flexural strength, permeability, compressive strength, tensile strength, and porosity, the effects of cement-water ratio, aggregate gradation, and fine aggregate percentage are estimated. Different samples of pervious concrete mixtures have been produced and experimentally tested employing aggregate sizes of 20–16 mm, 16–12.5 mm, and 12.5–4.75 mm. In the study, the water-cement ratio is considered between 0.30 and 0.32. The presence of GGBS in the permeable concrete was evaluated using a systematic investigation of the compressive strength and permeability properties. In this experimental initiative, it is suggested that GGBS may be utilized to partially replace cement. The percentages of replacement were considered as 25 percent, 30 percent, 35 percent, and 40 percent. The combination started to lose its stability once we reached the maximum level of 40%. The split tensile strength, flexural strength, and compressive strength were all improved with a 40% substitution. The GGBS has been raised, yet it has decreased permeability. The current study has improved the structural and hydrological properties of porous concrete by adding GGBS at a selected percentage, and this improved mix may be used for the preparation of porous concrete layers for low-volume road construction.

7.2 INTRODUCTION

Water, Portland cement, and coarse aggregate are the components of permeable concrete. Pervious concrete is considered a pavement because it has environmentally friendly aspects like hydrological and mechanical properties. The use of pervious concrete had been restricted to the construction of footpaths, walkways, parking lots, etc. But gradually, this concept has been implemented in carriageway construction. The challenge faced in this concept is to sustain the moving traffic load. Since pervious concrete is an open-graded pavement, it can allow water to percolate through it easily, but it must desperately withstand the traffic load. The lack of fine particles in the mix sets it apart from regular concrete. The aggregate is typically one size, and the point of contact is where a cement and water paste is used to bind the material together. To make a paste, a specific amount of water and cementitious materials are combined. When mixed and applied, the paste creates a thick layer over the aggregate particles to prevent them from leaking. Pervious concrete creates a harsh mix that is challenging to mix and put down because it lacks fine aggregate. As a result, the concrete has a significant number of interconnecting voids. Water may swiftly percolate through concrete when it is appropriately constructed. Contrary to pervious concrete, which has a void ratio that can range from 15 to 40 percent, ordinary concrete has a void ratio of between 3 and 5 percent. Pervious concrete has a low weight (between 1600 and 2000 kg/m^3) because of its large void content. Depending on the use, the void ratio of pervious concrete varies. A large degree of surface ravelling and honeycombing may be seen on the pervious concrete's surface. Many studies have been performed to improve the strength of the pervious concrete layer. Aggregates of different sizes and shapes are used to develop the strength parameters of porous concrete. Different types of additives, including polypropylene fiber, polyethylene fibers, and fly ash, have been used to enhance the strength and durability attributes of pervious mix. To test the behavior of pervious concrete, overburnt brick aggregate has also been employed as coarse aggregate. Different mix designs have been tested and compared to see how previous concrete performed in terms of its strength and hydrological qualities.

In earlier research, it was observed that although pervious concrete is an open-graded pavement, if it has satisfactory bonding with the aggregates, it can resist traffic loads as well as allow percolation of water. GGBS is a material that has the cementitious property to have good bonding in the mix. In order to produce ground-granulated blast furnace slag, iron slag is quenched from the source of blast furnace molten iron in aqueous media to create a glassy, granular by-product that is further dried out and pulverized into fine powder. When added to concrete, GGBS enhances its workability, strength, and durability. Infiltration characteristics have also been examined in the current study. The flexural and compressive strengths of the concrete reportedly increased, and the percolation of water was maintained when up to 40% of the cement was replaced with slag, according to the authors.

7.3. MATERIALS AND METHODS

In this investigation, GGBS is used to partially replace the cement. Different tests have been initially performed to ascertain the physical characteristics of materials. Concrete mixes have been prepared with and without GGBS by replacing cement partially. Ten mix variations were formed using water-cement ratios of 0.30 and 0.32. The aggregate-to-binder ratio adopted in the study was 1:4. M1, M2, M3, M4, M5, M6, M7, M8, M9, and M10 are the assigned mix combinations. Using the above-mentioned mix preparation, testing has been done to assess the behavior of hardened concrete.

7.3.1 Materials

The materials used in this research are as follows:

• **Cement**: Different types of construction materials are joined together using cement as a binding agent. It typically comes from limestone and evolved from other varieties of hydraulic lime in England in the middle of the 19th century. It is a fine powder that is created when materials are heated to create clinker. The additional ingredients are gradually added once the cement has been ground. All standards for standard compliance should be met by the cement. Portland Pozzolana Cement was employed in this investigation.

• Fine aggregate:

In this study, gaps have been filled and strength was increased by using readily accessible local sand. In comparison to the weight of coarse aggregate, 5% of fine aggregate has been utilised. The only mix combinations that contain fine aggregate are M2, M7, M8, M9, and M10.

• **Coarse aggregate**: Different kinds of construction materials are joined together by the binding agent cement. It typically comes from limestone and evolved in England in the middle of the 19th century from other varieties of hydraulic lime. When materials are heated to create clinker, a fine powder is created. The final elements are added in modest amounts after the cement has been ground. All specifications set forth in the standards should be met by the cement. Portland Pozzolana Cement was employed in this investigation. The strength of the concrete and its constituent components are not the only clues. However, in pervious concrete, the amount of cement paste is constrained, and the aggregate's strength comes from the surfaces that come into contact with one another. So an aggregate that is harder, like granite, would produce more compressive strength than an aggregate that is softer, like limestone. As coarse aggregate, over burnt aggregates are also used in the preparation of mix (Debnath and Sarkar, 2020). Crushed aggregate that is readily available locally has been employed in the study as a coarse aggregate. The aggregate used in this investigation is granite stone. Three aggregate sizes were used: 25% of 16 mm to 12.5 mm, 50% of 12.5 mm to 4.75 mm, and 50% of 20 mm to 16 mm.

Table 7.1 Mix designations

Mix designation	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Cement (%)	100	100	75	70	65	60	75	70	65	60
GGBS (%)	0	0	25	30	35	40	25	30	35	40
Fine aggregate (%)	0	5	0	0	0	0	5	5	5	5

Table 7.2 Cement properties

% Of Fineness	Specific Gravity	Standard Consistency (%)	Setting Time (Initial) (In Min)	Setting Time (Final) (In Min)	Compressiv eStrength (MPa)
5.1	3.14	32	90	435 min	39

Table 7.3 Coarse Aggregate Properties

Impact Value (%)	Crushing Value (%)	Los Angeles Abrasion Test (%)	Water Absorption (%)	Specific Gravity	Flakiness Index (%)	Elongation Index (%)
10.52	12.36	21.65	2.06	2.80	31.38	45.29

Table 7.4 Chemical compositions of cement and GGBS

Chemical Constituent	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	LOI	NaO	SO_3
GGBS	41.97	10.66	35.44	8.13	0.37	3.13	-	0.33
Cement	62.9	4.89	19.87	2.53	2.34	2.57	0.77	3.8

- **Ground granulated blast furnace slag (GGBS):** A glassy, granular product that is then crushed and dried into a fine powder is created by condensing molten iron slag from a blast furnace in water or steam. A by-product of the production of iron and steel is molten iron slag. The "Ground Granulated Blast Furnace Slag" (GGBS) by-product of manufacturing iron improves the workability, durability, and strength of concrete when added to it. The substance is made by heating iron ore, limestone, and coke to a temperature of about 1500°C. The process happens in a blast furnace. The GGBS did not directly form. Molten iron and molten slag are by-products of the production of iron. A small amount of oxides, as well as silica and alumina, make up the molten slag. Later, the slag is granulated through cooling. It is permitted to do so by passing through a high-pressure water source. The quenching of the particles produces granules with a diameter less than 5 mm as a result. Blast furnace slag is mostly composed of CaO, SiO_2, Al_2O_3, and MgO. Most cementitious materials contain these particular minerals. To create ground granulated blast furnace slag, the particles are further dried and ground in a spinning ball mill. Now, various techniques can be used to carry out the main procedure known as quenching.

- **Water:** Pervious concrete's strength is mostly due to the contribution of water. The least expensive but most crucial component of concrete is this. Concrete should generally be made with potable water that is safe for consumption. It should range from 6 to 9 on the pH scale. Concrete is mixed with water, and water is also used to cure the concrete. Concrete should only be made using clean, contaminant-free water that is devoid of harmful substances like oil, alkali, acid, and other pollutants. The combination has been made using tap water from our campus.
- **Superplasticizer:** Superplasticizers are the additives that are used to prepare the higher strength concrete. This is also called as water reducers of high range. These are the chemical ingredients that allow concrete to be made with 30% less water. The superplasticizer (AURAMIX 200) employed in this investigation is based on polycarboxylate ether. Depending on the weight of the cement, it is mixed with water at a rate between 0.7% and 0.8%.

7.3.2 Mix Proportioning:

The mix proportioning technique is based on the absolute volume idea and adheres to specifications stated in ACI 522R-10 and IS 10262:2019. Next, the necessary void volume is assessed. The total volume of aggregate is calculated by subtracting the volume of paste and the volume of voids from the unit volume of concrete. The ratios of fine and coarse aggregate volumes are then selected. Based on field data found in the literature, an experimental setup has been established with water ranging from 132 kg/m^3 to 141 kg/m^3 and cement levels of 439 kg/m^3 as a practical range taken into account for ordinary concrete. The study has been done with two w/c ratios of 0.30 and 0.32. The void of 15% has been selected and is considered for all types of mixes. To satisfy the dual essential criteria of acceptable strength and permeability, a fine aggregate composition of 5 percent has been employed.

Table 7.5 Mix proportions with water cement ratio 0.3 and superplasticizer 0.8%

Mix Designation	Cement	GGBS	Water	Fine Aggregate	Coarse Aggregate	Super Plasticizer
M1	439	0	98.775	0	1756	3.512
M2	329.25	109.75	98.775	0	1756	3.512
M3	307.3	131.7	98.775	0	1756	3.512
M4	285.35	153.65	98.775	0	1756	3.512
M5	263.4	175.6	98.775	0	1756	3.512
M6	439	0	98.775	87.8	1756	3.512
M7	329.25	109.75	98.775	87.8	1756	3.512
M8	307.3	131.7	98.775	87.8	1756	3.512
M9	285.35	153.65	98.775	87.8	1756	3.512
M10	263.4	175.6	98.775	87.8	1756	3.512

Table 7.6 Mix proportions with water cement ratio 0.32 and super plasticizer 0.7%

Mix Designation	Cement	GGBS	Water	Fine Aggregate	Coarse Aggregate	Super Plasticizer
M1	439	0	105.36	0	1756	3.073
M2	329.25	109.75	105.36	0	1756	3.073
M3	307.3	131.7	105.36	0	1756	3.073
M4	285.35	153.65	105.36	0	1756	3.073
M5	263.4	175.6	105.36	0	1756	3.073
M6	439	0	105.36	87.8	1756	3.073
M7	329.25	109.75	105.36	87.8	1756	3.073
M8	307.3	131.7	105.36	87.8	1756	3.073
M9	285.35	153.65	105.36	87.8	1756	3.073
M10	263.4	175.6	105.36	87.8	1756	3.073

- All Proportions are in kg/m^3

7.3.3 Sample Preparation

The samples have been prepared with a pan mixer. The dry mix, namely cement, GGBS, fine aggregate, and coarse aggregate, has been mixed for an additional two minutes, along with the addition of water and superplasticizer. The entire mixing process has been done for four (4) minutes for each attempt until the formation of a homogeneous mixture. The mixes have been compacted by a regular tamping rod, and it has been ensured that the moulds have been filled in layers with the proper number of blows. Each of the mixes has been prepared in the same manner. For curing, the samples have been submerged under water for 7 and 28 days.

7.3.4 Methodology

7.3.4.1 Tests on Coarse aggregate:

- **Sieve analysis of Aggregate: (IS 283-1970)**

Sieve analysis is carried out to ascertain the coarse aggregate's particle size distribution.

Figure 7.1 Sieve analysis

- **Specific Gravity and Water Absorption (%): IS: 2386 (Part-3)**

The specific gravity of an aggregate is defined as the mass of the solid in a given volume of sample divided by the mass of an equivalent volume of water at 4°C. All rocks do, however, contain a little bit of space, and the apparent specific gravity takes this space into account. The specific gravity of a material's aggregates can be used to determine its density and quality. Low specific gravity might indicate substantial porosity, which would correlate to poor toughness and weak durability. Information on the relative density and absorption of water by the coarse particles is needed for the design of the concrete mix. A useful indicator of an aggregate's quality and characteristics is its specific gravity. If the specific gravity differs from the value generally assigned to a certain type of aggregate, it may indicate that the aggregate's grading and form have changed. Additionally, it is crucial in many calculations related to concrete mix design and moisture contact determination. Additionally, it is necessary for the estimation of concrete's volume yield.

Figure 7.2 Pycnometer method

- **Aggregate Impact Value: IS 2386 (part 4)**

Toughness is the property of a substance that allows it to endure the impact. Due to traffic loads, the road stones are exposed to the pounding action of impact, and there is a possibility that they will shatter into smaller pieces. In order to sustain contact without shattering, the road stone must be robust enough. A road stone's toughness, or its ability to withstand breaking under repeated blows, can be evaluated using an impact test. In contrast to its resistance to a steady, gradually growing compressive force, the aggregate impact value provides a relative assessment of an aggregate's resistance to a quick shock or impact. The process for calculating the total impact value is covered by the test method for coarse aggregate.

Figure 7.3 Aggregate impact testing machine

- **Aggregate Crushing Strength: IS 2386 (part 4)**

Road stone's crushing strength can be assessed using either aggregates or cylinder-shaped rock specimens. The two exams differ significantly in terms of approach as well as how the findings are presented. Aggregate used in road building must be hard enough to withstand being crushed by rolling wheels. If the aggregates are poor, the durability of the pavement construction is going to suffer. The strength of coarse aggregates is assessed using the aggregate crushing test. The capacity for resistance to crushing against a crushing load that occurs gradually is indicated by the aggregate crushing value. If you want a pavement with a high level of quality, you should choose aggregates with a low aggregate crushing value.

Figure 7.4 Aggregate crushing strength testing machine

- **Los Angeles Abrasion Value: IS 2386 (Part 4)**

The goal of the Los Angeles Abrasion Test is to determine the percentage of wear resulting from the relative rubbing action between the aggregate and the steel balls employed as the abrasive charge. These balls also exert a hammering action as the test is conducted. Some researchers think that this test is more accurate since the rubbing and hammering mimic real-world situations where both abrasion and impact can happen. The ASTM, AASHTO, and ISI have all standardized the Los Angeles Abrasion Test. There are also standard Los Angeles Abrasion values available for a range of pavement constructions.

Figure 7.5 Los Angeles abrasion testing machine

- **Flakiness Index and Elongation index: IS 2386 (Part 1)**

The flakiness index is the proportion of aggregated particles whose thin dimension (thickness) is less than three fifths of their mean dimension. Sizes smaller than 6.3 mm cannot be tested.

The elongation index of an aggregate is the percentage of particles in the aggregate with a largest dimension (length) more than 1.5 (1.8) times its mean dimension. The elongation test does not apply to sizes less than 6.3 mm.

Figure 7.6 Elongation and Thickness gauge

7.3.4.2 Tests on concrete

- **Compressive Strength**

Compressive strength is a crucial feature of concrete. Compressive strength of concrete is inversely connected to all of its other properties. This test can be used to determine whether concrete pouring was done correctly or incorrectly. Utilised is a cubical mould with dimensions of 15 cm, 15 cm, and 15 cm. After curing for 7 days and 28 days, respectively, the cubes were tested using a compression testing apparatus.

- **Split tensile strength:**

Split tensile strength is used to calculate the development length of the reinforcement and analyse the shear resistance of the concrete while developing structural lightweight concrete components. Using this test method, a diametrical force is applied down the length of a concrete cylinder until failure occurs within the predetermined limit. The highest force that the specimen could withstand is multiplied by the appropriate geometrical variables to determine the split tensile strength. The height and diameter of the cylindrical mould is 200 mm and 100 mm respectively.

- **Flexural strength:**

The resistance of a concrete beam to breaking when bent is known as flexural strength. For testing, 50 cm-long concrete beams are loaded to assess their strength. This test is carried out using an experiment with four loading points. Forces are applied to the four different places during the four-point loading test. Five centimeters from the ends, the beam is supported at two locations below. The dimensions are typically 15 × 15 × 70 cm. Alternately, specimens 10 × 10 × 50 cm may be used if the aggregate nominal size is less than 19 mm.

- **Permeability:**

In this study, the falling head permeability test apparatus was used to evaluate the permeability property of porous concrete specimens. The permeability test set-up is the consistency of a graduated cylindrical tube to measure the hydraulic heads and valves to control water flow. The setup has a steel mold to retain the specimen and an above-ground tank for continuous water delivery. The duct tape has been used to steal the concrete specimen in order to stop any lateral water movement. A commercially available water-proof sealant substance has been used to cover the joint where the specimen and the cylinder meet. By alternately controlling the valves, the specimen has been given time to thoroughly soak in water prior to the test. This is done to make sure the specimen doesn't contain any air voids.

$$k = \frac{2.3al}{At} \log\left(\frac{h_1}{h_2}\right)$$

Where, K = Permeability in cm/s, l = length of specimen in cm, a = sample’s cross-sectional area in cm^2, A= surface area of stand pipe, h_1 = initial water head in mm, h_2 = ultimate water head in mm, t = time in sec.

➢ **Porosity:**

The ASTM D 1754 water displacement technique has been used to assess the porosity by using specimens of cylindrical shape with a diameter of 100 mm and a height of 200 mm. By calculating the difference between the dry and submerged weights, the porosity has been estimated. After the proper curing of all the samples, their submerged heights have been recorded. Then the samples were kept dry in the thermostatically controlled oven at 110° C for 24 hours. The formula listed below is used to calculate the porosity property.

$$\phi = \left[1 - \frac{(A - B)}{\rho_w \times D^2 \times L}\right] \times 100$$

Where, Ø = porosity of the mix; A = dry weight of the specimen; B = submerged weight of the specimen; ρw = density of water; D = average diameter of specimen; L = length of the specimen.

7.4 RESULTS AND DISCUSSIONS:

Different tests like compressive strength, split tensile strength, flexural strength, porosity, and permeability have been conducted on porous concrete. All the tests demonstrate the effects of cement replacement with GGBS in varied percentages after the curing for the period of 7 and 28 days.

Table 7.7 Results of permeable concrete with w/c ratio 0.30 after 7days curing period

Designation of Mix	Strength (Compressive) (MPa)	Strength (Split Tensile) (MPa)	Strength (Flexural) (MPa)
M1	14.279	1.442	2.281
M2	11.289	1.398	2.275
M3	15.178	1.466	2.362
M4	17.252	1.429	2.438
M5	18.943	1.527	2.403
M6	17.740	1.396	2.471
M7	17.873	1.407	2.518
M8	19.686	1.462	2.661
M9	20.398	1.558	2.703
M10	20.483	1.711	2.794

Table 7.8 Results of permeable concrete with w/c ratio 0.32 after 7days curing period

Designation of Mix	Strength (Compressive) (MPa)	Strength (Split Tensile) (MPa)	Strength (Flexural) (MPa)
M1	13.478	1.223	2.127
M2	12.384	1.191	2.045
M3	15.600	1.424	2.442
M4	18.632	1.341	2.717
M5	13.498	1.318	1.312
M6	16.245	1.327	2.498
M7	16.158	1.336	2.512
M8	18.424	1.380	2.762
M9	19.421	1.506	2.787
M10	15.365	1.520	2.007

Tests were done on the samples after the 7-day curing period, considering the w/c ratios of 0.30 and 0.32 as shown in Tables 7.7 and 7.8. From the results, it is observed that the mix (M10) containing 40% cement replacement by GGBS and 5% fine aggregate gave considerably higher strength in all three tests at a water-cement ratio of 0.30. The partial replacement of cement by GGBS gives satisfactory result from the test performed in this work (A.A. Phul et al. 2019).

Table 7.9 Results of porous concrete samples with water-cement ratio 0.30 after 28 days curing period

Designation of Mix	Strength (Compressive) (MPa)	Strength (Split Tensile) (MPa)	Strength (Flexural) (MPa)	Porosity (%)	Permeability (cm/s)
M1	20.605	1.825	2.521	24.89	2.24
M2	16.290	1.625	2.636	27.12	2.41
M3	21.902	1.842	2.629	24.51	2.19
M4	24.895	1.809	2.657	23.27	2.11
M5	27.335	1.898	3.075	20.75	1.86
M6	25.598	1.767	3.244	20.2	1.83
M7	25.790	1.781	3.358	19.37	1.75
M8	28.406	1.851	3.676	16.74	1.56
M9	29.435	1.876	3.841	13.21	1.33
M10	29.557	2.086	3.814	13.48	1.29

Table 7.10 Results of porous concrete samples with water-cement ratio 0.32 after 28 days curing period

Designation of Mix	Strength (Compressive) (MPa)	Strength (Split Tensile) (MPa)	Strength (Flexural) (MPa)	Porosity (%)	Permeability (cm/s)
M1	18.851	1.487	2.351	26.53	2.38
M2	17.320	1.500	2.370	26.47	2.26
M3	21.819	1.720	2.595	24.22	2.14
M4	26.058	1.640	2.961	21.96	1.89
M5	18.879	2.019	1.679	19.89	1.76
M6	22.720	1.816	3.279	22.48	1.96
M7	22.598	1.780	3.350	23.71	2.02
M8	25.768	1.822	3.816	19.77	1.74
M9	27.162	2.020	3.960	17.62	1.61
M10	21.489	1.880	2.740	14.83	1.38

Samples were also tested after the curing period of 28 days considering the w/c ratios of 0.30 and 0.32 as shown Table 7.9 &7.10. From the results, it is observed that the mix (M10) containing 40% GGBS and 5% fine aggregate gave higher strength and considerable permeability.

Different properties of pervious concrete with respect to varying percentage of GGBS as partial replacement of cement have been presented graphically.

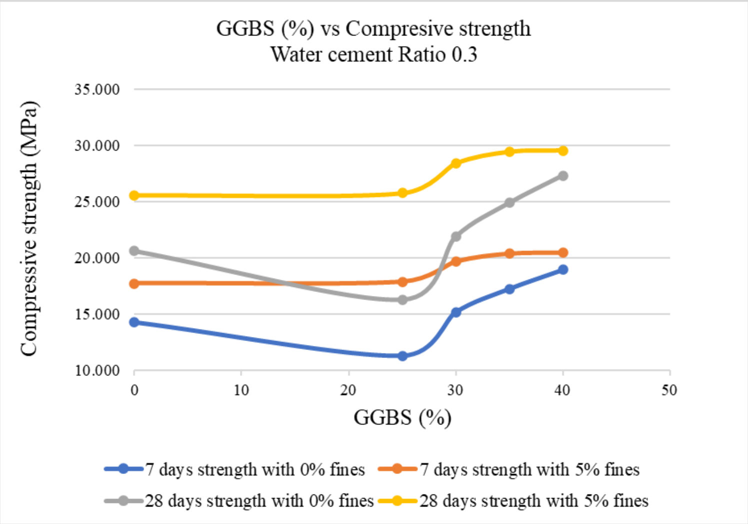


Figure 7.7 GGBS (%) vs Compressive Strength

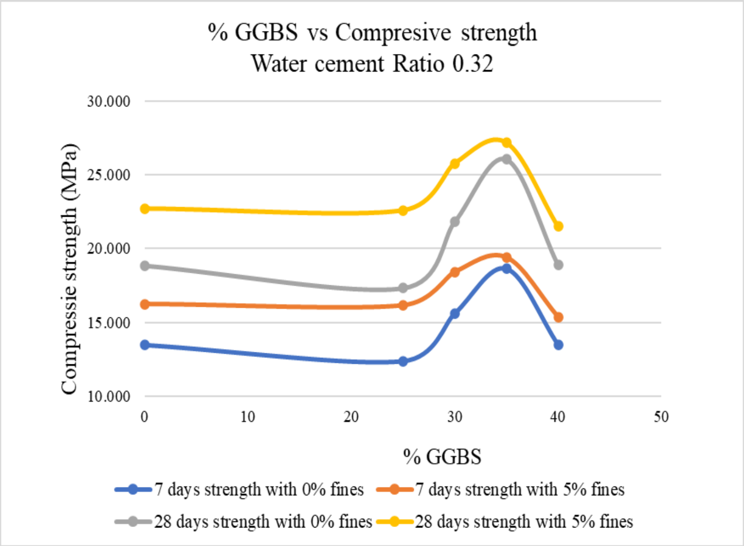


Figure 7.8 GGBS (%) vs Compressive Strength

In the Figures 7.7 & 7.8, it is observed that after 28 days the crushing strength is maximum at 5% fines and 40% cement replacement by GGBS with water cement ratio 0.30. And least compressive strength is obtained after 7 days curing with 0% fines and 25% cement replacement by GGBS at same water cement ratio.

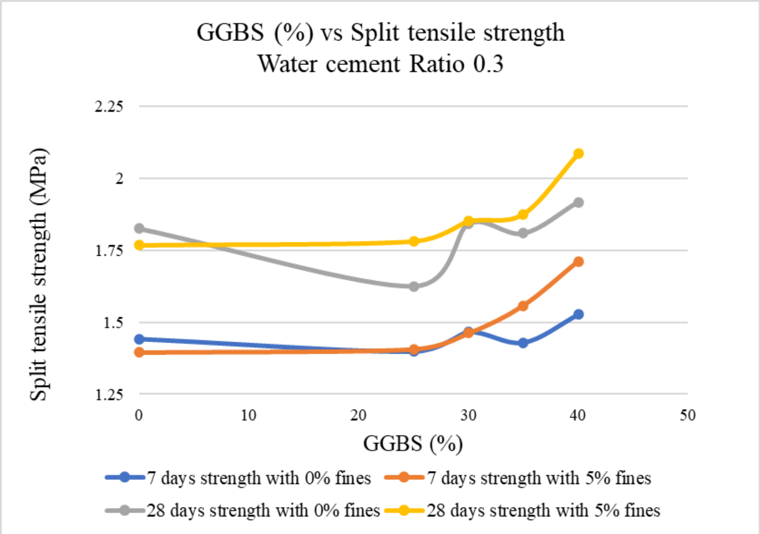


Figure 7.9 GGBS (%) vs Split Tensile Strength

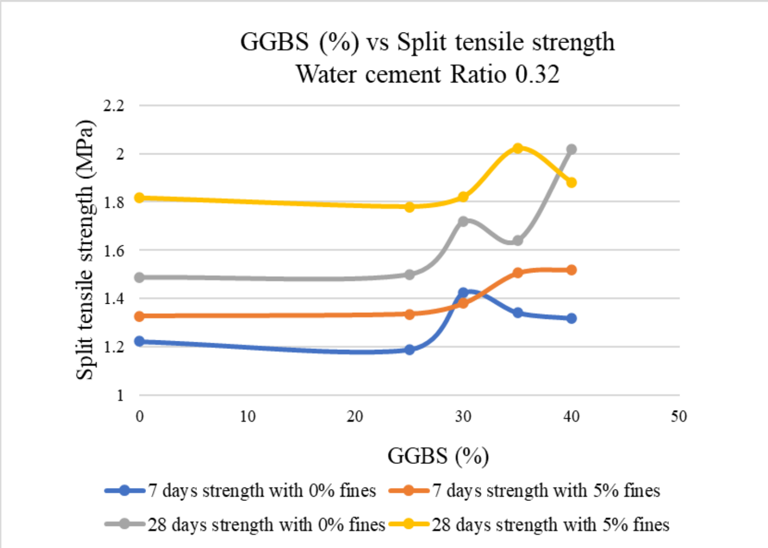


Figure 7.10 GGBS (%) vs Split Tensile Strength

From the Figures 7.9 & 7.10, it has been observed that maximum split tensile strength is obtained after 28 days curing 5% fines and 40% cement replacement at water-cement ratio of 0.30.

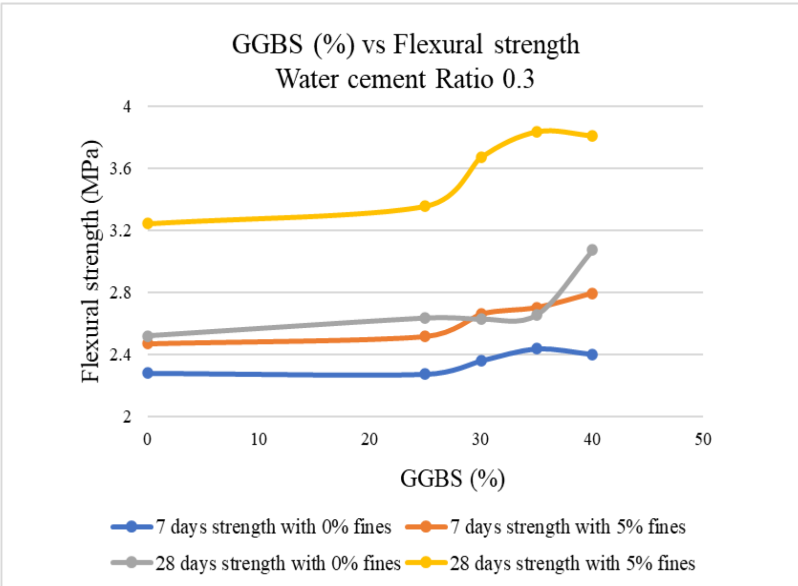


Figure 7.11 GGBS (%) vs Flexural Strength

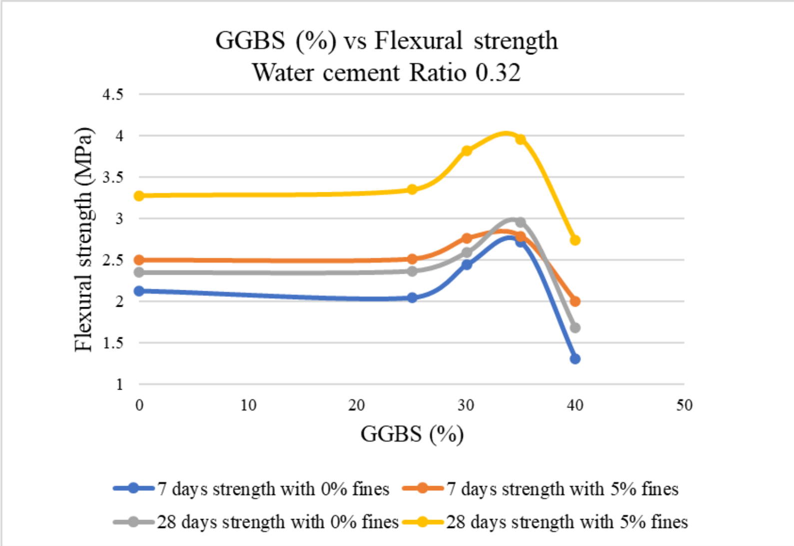


Figure 7.12 GGBS (%) vs Flexural Strength

From the Figures 7.11 & 7.12, it has been noticed that after 28 days curing the flexural strength is maximum at 5% fines and 35% cement replacement. Although the maximum value has been attained for the water-cement ratio of 0.32, but substantial value has been attained for the same mix at water-cement ratio of 0.30. From the tests results of strength, it is observed that use of GGBS in the mix as partial replacement gives acceptable results (V.R. Suda, 2020).

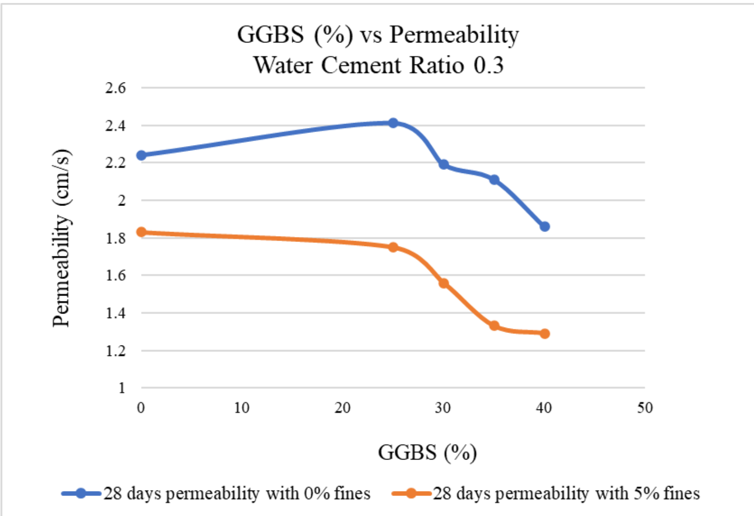


Figure 7.13 GGBS (%) vs Permeability

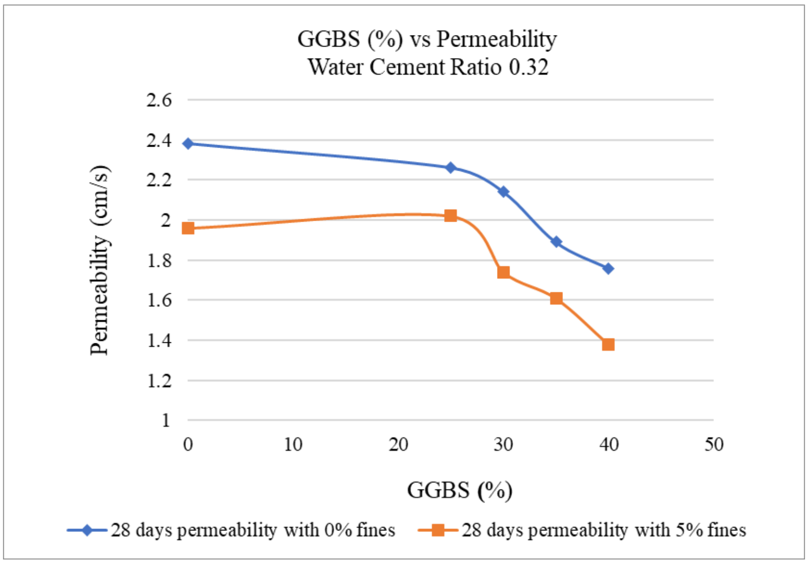


Figure 7.14 GGBS (%) vs Permeability

Permeability property of the mixes is checked after 28 days curing. From the Figures 7.13 &7.14, it is observed that the mix with 0% fines shows maximum value with 25% cement replacement at water-cement ratio of 0.30.

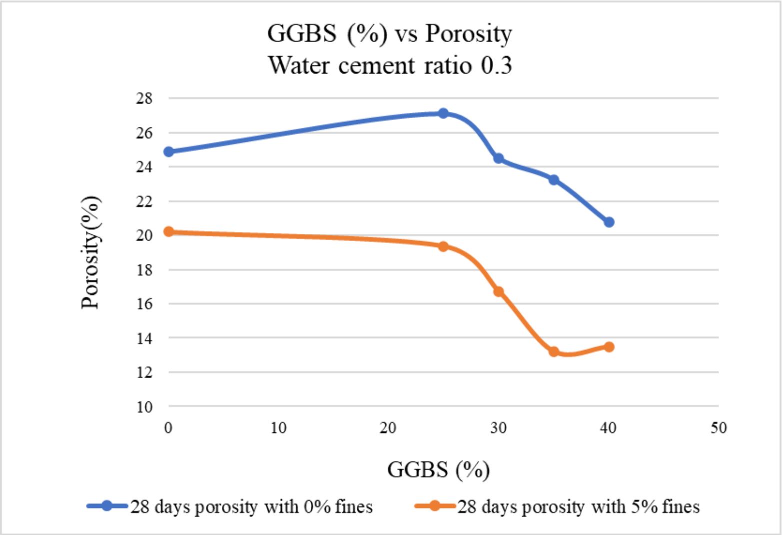


Figure 7.15 GGBS (%) vs Porosity

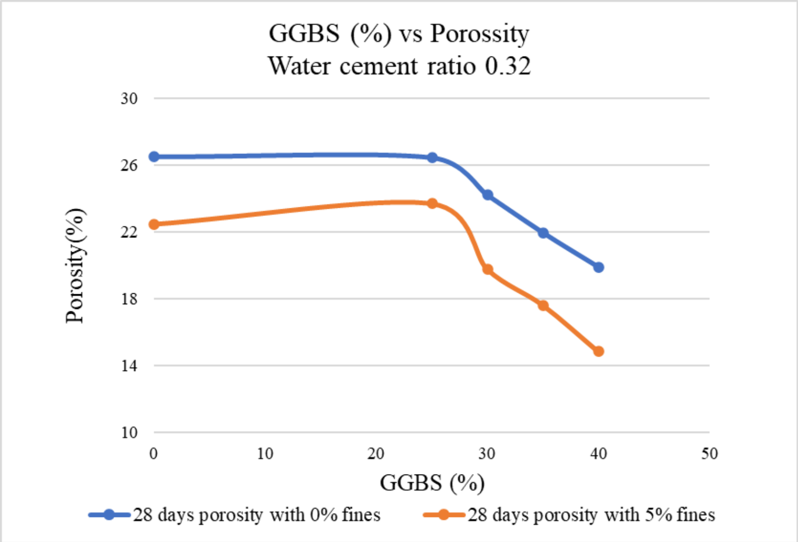


Figure 7.16 GGBS (%) vs Porosity

From figures 7.15 & 7.16, it is observed that in terms of porosity, the mix with 0% fines and 25% cement replacement after 28 days curing at water-cement ratio of 0.30 shows the maximum value and mix with 55 fines with 40% cement replacement at same water-cement ratio shows the least value.

7.5 Findings of the study

In this study, GGBS is added to the mixes at different percentages as a partial cement replacement. Fine particles are also added to the mix. Mixes have been cast with two types of water-cement ratios, viz., 0.30 and 0.32. Various examinations, including flexural strength, crushing strength, permeability, and split tensile strength tests, are carried out on the mix samples. From the experimental study, it is seen that with strengths like crushing strength and split tensile strength, the maximum value is obtained when 40% cement of the mix is replaced by GGBS and 5% fine aggregates are added at a w/c ratio of 0.30. It has also been noticed that the maximum value for flexural strength is found for the mix having 35% cement replacement and 5% fines at a water-cement ratio of 0.32 after 28 days of curing. In terms of permeability, a mix having 0% fines with 25% cement replacement at a water-cement ratio of 0.30 shows the maximum value. So it may be concluded from the observations that the addition of GGBS in a higher percentage along with fine aggregates improves the mix in terms of different strength parameters, but permeability and porosity properties are decreased at the same time. So, based on the previous and current research, it may be stated that GGBS is one of the alternatives to use in pervious concrete mixes as cementitious material, and it can improve the strength and hydrological properties of the mix.

CHAPTER- 8

UTILIZATION OF POROUS ASPHALT MATERIAL IN ROAD CONSTRUCTION FOR REDUCING THE VEHICULAR NOISE

8.1 General

Porous asphalt (PA) material can be used as a wear surface for building roadways. In order for rainwater to efficiently permeate into the soil, it must first drain through a porous asphalt layer that is extremely permeable and unobstructed. The subsurface water layer should not be disturbed, and the lowest layers must have enough room to hold the volume of water. Numerous impurities might be eliminated as a result of the permeable asphalt layer being penetrated by rainwater. Stone beds and soils can help filter out toxins. One of the environmental sources that might harm human health in metropolitan settings is noise. According to the World Health Organization (WHO), noise levels above 70 dB (A) can harm hearing. Additionally, it causes hypertension and anxiety. One of the main causes of the noise pollution caused by cars is the roughness of the pavement. In past research, the noise levels produced by autos received some attention, which was more concerned with the impact of different pavement types on the local acoustic environment of roadways. Moving cars on paved roads induces friction between the pavement's surfaces and the tires, which results in noise pollution. Therefore, a noise-cancelling surface approach can help lessen the issue. Porous asphalt is a creative method of building roads with a noise-cancelling surface. When there are air holes, the asphalt layer might be penetrated by water. This kind of pavement can lessen road surface sloppiness and traffic noise (Mann and Singh, 1995). The characteristics of the design and the technology employed in it determine the efficacy of the porous asphalt pavement. The inter-air space that is maintained in the pavement layers is primarily responsible; this method may also be applied in areas with high design requirements and significant traffic. Permeable pavement can be used on established roads, driveways, low-volume highways, footways and pathways, parking areas, and other places (Tiwari et al. 2017). The level of noise produced by pervious pavement is lower than that of conventional asphalt pavement. The current study focuses on (a) measuring the amount of noise generated by traffic at a few distinct sites in the city of Agartala, (b) examining vehicle movement at various areas within the city of Agartala, and (c) comparing the two types of asphalt pavement. The aforementioned goals were achieved by doing a noise level survey on the city's highways in Agartala. Additionally, the amount of traffic on various roads in the city of

Agartala has been measured, and the resulting noise level has been recorded. The effectiveness of the porous asphalt pavement in reducing noise levels was then tested by comparing it to regular asphalt pavement.

8.2 Porous asphalt pavement

Porous asphalt pavement and conventional densely graded asphalt are very different from one another. The gradation of aggregates in the various layers ranges between typical hard asphalt roads and permeable asphalt roads. More coarse aggregate is used in porous pavement than fine aggregate. There are therefore more air spaces in porous asphalt pavement. The following describes the many pavement layers made of porous asphalt:

- Layer I: Surface Course

This layer has a thickness of 50 to 100 mm. The aggregate variation is selected to leave between 16 and 22% of an air void following compaction. Water can percolate through the road surface thanks to the air gaps between the aggregate particles.

- Layer II Choking Course

This layer is made up of aggregates that are retained on a 12.5-mm sieve and pass through a 16-mm sieve. This layer might be anywhere between 25 and 50 mm thick; about 20 and 30 percent should be left as an air void.

- Layer III: Reservoir Course

The stone reservoir course temporarily stores rainwater. After that, the rainwater gently seeps into the natural subgrades. Between 200 and 300 mm thick, the layer Aggregates with a uniform grading range of 40 to 75 mm have been employed. They function as water storage. To enable rainwater percolation, this layer has to have 30–35% voids.

- Layer IV: Geotextile Sheet Layer

Roads have been covered in geotextile material to encourage water percolation. This sheet is used to create a barrier between the soil subgrade and the reservoir channel. Additionally, it makes sure that no soil from the subgrade enters the reservoir channel. If aggregate gradation control is good, stone filler with aggregate sizes of 10 to 25 mm and a thickness of 75 mm can be utilized as an option.

- Layer V: Uncompacted Subgrade

The natural layer is subgrade that has not been compacted. This soil layer is maintained undisturbed for permeability. The subgrade is kept at a slope of less than 5%. The infiltration rate of the soil varies from 2.5 mm/h to 76 mm/hr. Porous asphalt pavement construction is not likely to be employed on subgrades that include clay.

8.3 Study area

The state of Tripura's capital is Agartala. Environmental contamination is rising in Agartala city as a result of rapid urbanization and a large increase in traffic volume. The noise made by various vehicles is a significant factor in this pollution. According to the research, the typical noise levels are between 60 and 100 dB (A) at night and 80 to 110 dB (A) during the day, respectively, and these values fall below the Indian Standard for Ambient Noise Levels. To reduce noise levels, permeable asphalt surfaces may be used in several areas in Agartala city, including parking lots, low-traffic roads, etc.

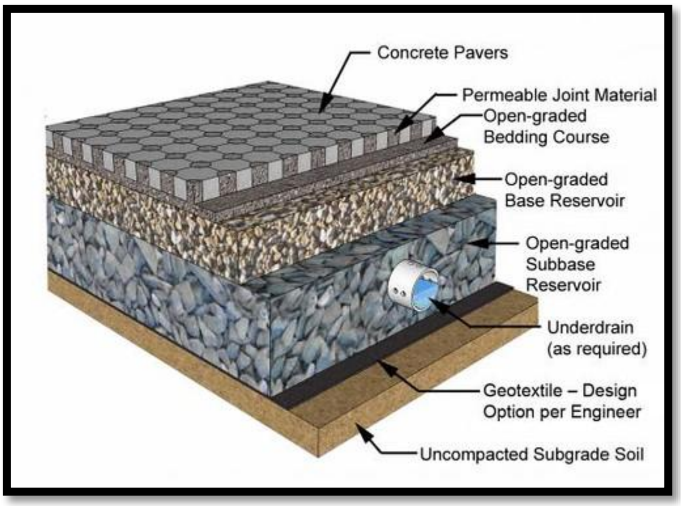


Figure 8.1 Typical permeable asphalt pavement layer details.
[Source: https://www.flickr.com/photos/fossil_lin/12586220794]

8.4 Materials & Methodology

Aggregate, bitumen, and plastic (LDPE) are the ingredients needed to create a mix of modified bituminous concrete. Plastic carry bags are utilized because they are made of plastic. (LDPE): Light-density polyethylene, which is used to make plastic carry bags, is widely accessible. Various tests are carried out in order to ascertain the physical characteristics of regular aggregates and aggregates with plastic coatings (PCA). Table 8.1 presents the findings from these tests. In order to calculate the ideal binder content (OBC) of bituminous mixes, the Marshall Mix technique has been used. Rock aggregates are plastic-coated at concentrations of 0.25%, 0.5%, 0.75%, and 1%, and samples are then generated in accordance with the concentrations and the stability of the porous asphalt material's OBC and marshal. Marshall According to test results, unaltered porous pavement does not fulfill the MORTH standards' minimal requirements for stability. Additionally, it has been noted that a mixture of porous asphalt reached its maximum value and complied with the MORTH criterion at 0.5% plastic content [Table 8.2]. Table 8.3 lists the outcomes of porous asphalt pavement constructed from stone aggregate with varying levels of plastic coating and demonstrates the resilience of an asphalt porous mix at various levels of plastic content.

The seven routes in Agartala city where the noise level study was carried out were Akhaura Road, Hari Ganga Basak Road, VIP Road, Thakur Pally Road, Lakshmi Narayan Bari Road, and Old Motor Stand Road. In Agartala, there is a variety of traffic, including trucks, buses, minibuses, cars, jeep paddle cycles, and paddle rickshaws. Vehicle noise is assessed under diverse traffic conditions. A study was conducted on a few chosen roadways to gauge the volume of traffic from 5 A.M. to 11 P.M. Both daytime and night time noise levels for these routes are approximated. On each side of the road, two sound intensity meters have been installed to measure the noise level and capture the noise produced by cars traveling in both directions at once. According to this poll, there were significantly fewer vehicles between the hours of 11 P.M. and 5 A.M. For an 18-hour period (from 5 A.M. to 11 P.M.), assessments of the level of noise and traffic volume are therefore calculated. Because there are so few cars on the road, the rest of the time has been disregarded.

Figure 8.2 (a) Stone aggregate, (b) Bitumen (VG-30), (c) Shredded plastic, (d) Shredded plastic on aggregate & (e) Plastic coated aggregate.

Table 8.1: Properties of regular aggregate and plastic-coated aggregate (PCA).

Name of the Tests	Regular Aggregate	Results % Plastic			Specifications of IRC: 111–2009
		0.50%	0.75%	1%	
Specific Gravity	2.76	2.79	2.83	2.85	2.5–3.0
Water Absorption	1.38%	0.93%	0.75%	0.62%	Less than 2%
Los Angeles Abrasion	29.32%	26.57%	25.18%	24.12%	Less than 40%
Impact test	23.27%	22.67%	22.11%	21.88%	Less than 24%
Crushing Strength	18.48%	17.82%	17.26%	17.13%	Less than 30%

Table 8.2: Design principles according to MORT&H.

Test Performed	Air Void (%)	VFB (%)	VMA (minimum) (%)	Minimum Stability at 60 °C (kN)	Flow (mm)	Marshall Quotient (kN/mm)
Results	3–5%	65–75	10	9	2–4	2–5

Table 8.3: Marshall Test results.

Sl. No	Parameter	Normal Aggregate	% Plastic			
			0.25%	0.5%	0.75%	1%
i.	OBC%	5.40	5.38	5.36	5.33	5.32
ii.	Marshall Stability(kN)	7.10	8.71	9.13	8.40	8.35
iii.	Flow(mm)	2.82	2.88	2.91	3.23	3.28
iv.	Unit weight (g/cm^3)	2.162	2.165	2.168	2.172	2.179
v.	% Air void	16.98	16.95	16.92	16.89	16.75
vi.	%VMA	27.02	26.84	26.52	26.33	26.03
vii.	%VFB	42.52	41.68	40.98	40.63	39.88
viii.	Marshall quotient(kN/mm)	2.52	3.02	3.14	2.60	2.55

Table 8.4 Indian Standards for Permissible Noise Levels.

Zone → / **Noise level dB (A)** ↓	**Silence Zone**	**Residential Area**	**Commercial Area**	**Industrial Area**
Day Time	50	55	65	75
Night Time	40	45	55	70

Comparable to 24-hour research, an 18-hour survey measures traffic in terms of typical daily traffic. To evaluate traffic noise levels, a test track made of permeable asphalt pavement was set up in the city area. Cars have been driving over it. The same procedure has been used for regular asphalt paving. Statistics on noise levels have been compiled based on the volume of traffic that went over the layer of porous asphalt.

8.4.1 Design of the noise trailer

The majority of research in the field conducted around the globe has centered on employing a noise trailer connected to the parent vehicle to measure tire road interface noise. Single, dual, and multiple-tyre vehicles with noise trailers have become popular. However, numerous researchers and organizations have started using dual-tire noise trailer assemblies with integrated microphones to record traffic noise. The authors started by doing a review of the current models for caravan noise. The extensive literature review helped with the development of a noise trailer for the study's research question. Then, information on the components, design, and manufacturing of the noise trailer is provided, along with a description of the genuine field highway sections in Bangalore used to assess tire and road noise levels. The design of the trailer in this study was based on a number of prior research studies and concentrated on a number of different factors, including the standard dual-tyre assembly contained in a noise-canceling chamber, the location of the noise meter in relation to the ground, tire pressure, and trailer weight. The layout designs for the caravan were produced utilizing the appropriate design and drawing tools. The caravan assembly was built to be substantial and hefty enough to support its own weight and react to medium and high traffic speeds quite effectively. The trailer's axle length was the same as the parent vehicle's axle length. The trailer's enclosure, or the acoustic chamber containing the axle and the tires, was built to impose its own weight on the axle, reducing the effect of the vehicle's vibrations and aerodynamics. To combat different pavement conditions, including cracking, potholes, surface degradation, and roughness, the concept also featured a minimal number of leaf-spring suspensions above the axle.

8.4.2 Noise trailer assembly

The noise trailer was built using the previously described components. The middle of the axle was welded to the steel shaft portion. The shaft on one side and the axle on the other were both joined by welding the angle supports. The leaves were then secured to the axle with two U-bolts, and a canter clip kept them all together. Steel rods were threaded into the leaf blades' eyes. The acoustic chamber, or steel casing, was welded to the steel rods. Bolts were used to line the PVC cushion on the inside of the acoustic chamber. This PVC cushion covered the whole top of the chamber and the surface of the road, leaving room on both sides. It was around 2 dB (A) quieter than without the cushion in situ.

8.4.3 Data collection

The noise trailer assembly and parent vehicle were driven across the AC, PCC, and PMAC types of roads with the primary goal of measuring the quantity of tire and road noise in the various parts of the city of Agartala. Test runs were carried out at the NIT Agartala campus (remember that this study was created and conceptualized at this College).

8.4.4 Decibel Scale

Time averaging and maximum value capture are the two most commonly used techniques for measuring noise. The kind of event will determine whether to average or use the maximum answer.

Time-averaging, for instance, is the ideal method for simulating the noise caused by a continual stream of traffic. On the other hand, applying the most pressure accurately captures the sound made by a single passing car.

8.4.5 Laboratory Testing

Due to the many voids present within porous pavement materials, noise levels can be decreased. The air movement is stopped or diminished when the sound wave encounters the solid walls of these spaces as it penetrates the material. Due to viscosity and heat conduction, some of the sound's energy is transformed into heat and dissipated. Although the porous pavement material does absorb some sound, a large percentage of the sound wave bounces back to the surface and travels into the air to produce noise. This is the way sound waves change and fade away. The standing-wave-tube method was used in a laboratory investigation to assess the acoustical characteristics of porous pavement material in order to maximize noise reduction. It is necessary to experiment with numerous mixtures of varying gradations and architectures.

8.4.6 Sound Level Meter

A sound level meter, or SPL, for short, is used to take acoustic measurements. It usually consists of a hand-held microphone device. The best type of microphone to use with a sound level meter is a condenser microphone since it offers precision, stability, and durability. The diaphragm of the microphones responds to changes in air pressure carried on by sound waves. As a result, the tool is sometimes called an SPL (sound pressure level) meter. An electrical signal (V) is produced by the diaphragm's movement (Pa) or fluctuation in sound pressure (Pa). Although it is possible to represent sound using sound pressure units like pascals, the sound level of pressure is usually measured instead after an exponential conversion.

Figure 8.3 An integrating-averaging cirrus Research's Optimus Sound Level Meter with IEC 61672-2

Sound level meters are frequently used in studies of noise pollution to quantify many types of noise, including noise from industry, the environment, traffic on roads, and aircraft. For this experiment, I utilized a Sound Level Meter with IEC 61672-2.

Table 8.5 Sound Level Meter Measurement

Description	Level
Level A-weighted equivalent	LAeq
Level A-weighted fast maximum	LAFmax
Level C-weighted slow minimum	LCSmin
Level Z-weighted impulse maximum	LZImax

The IEC Standard 61672-2 defines the various levels that are used to represent sound and noise level values. The first latter for levels is usually an L. This is a shorthand for level, which refers to the sound pressure level that can be detected by a microphone or the level that can be detected at the output of an audio component, such a mixing desk.

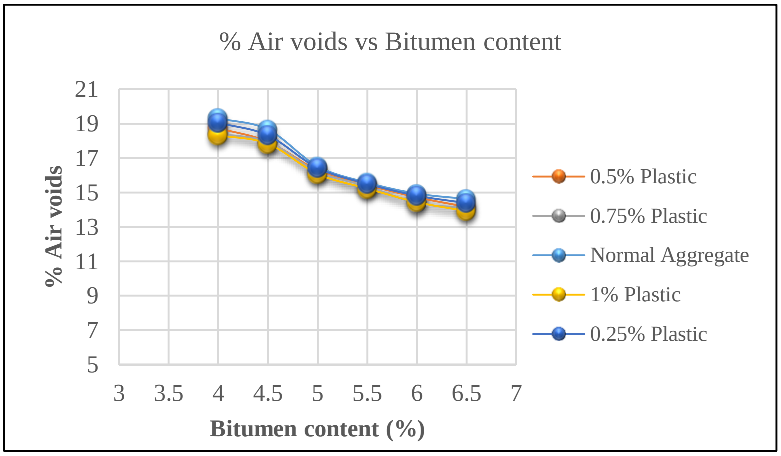
8.5 Results

To create the porous asphalt pavement, plastic was applied to the stone aggregates in four different percentages: 0.25%, 0.5%, 0.75%, and 1%. Marshall Test results are shown in Table 8.3. It is observed that porous pavement made with unmodified materials doesn't meet the minimum required stability as per MoRTH guidelines. It is also observed that at 0.5% plastic content, porous asphalt mix has achieved maximum value, which satisfies the MORTH specification [ref. Table 8.2]. Table 8.3 indicates the results of porous asphalt pavement made by plastic-coated stone aggregate at different percentages of plastic content. Figure 8.3 shows the results of the stability of the asphalt porous mix with respect to different percentages of plastic contents.

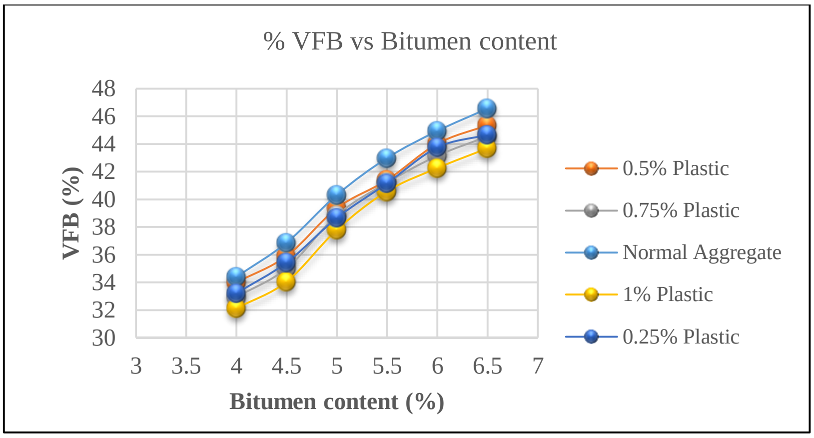
The noise level experienced by different categories of vehicles at various speeds in Agartala city is shown in Table 8.5. The noise level of mixed traffic on different roads in Agartala city during the day and night is shown in Table 8.6. From the study, it is observed that five categories of vehicles represent the traffic of Agartala city, and all categories of vehicles have a higher noise level on Conventional Asphalt Pavement as compared to Porous Asphalt Pavement with plastic coated stone aggregate. It is observed that on Conventional Asphalt pavement, vehicles have a noise level between 70 dB (A) and 83 dB (A), and on Porous Asphalt pavement, the same categories of vehicles have a noise level within the range of 66 dB (A) to 78 dB (A). This shows that Porous Asphalt Pavement with plastic-coated stone aggregate has a 4-5% noise reduction as compared to Conventional Asphalt Pavement. Out of all categories of vehicles considered in this study, motorcycles produce the least noise and trucks produce the most noise, as shown in Figure 8.5. In Figure 8.6, it is seen that using the porous asphalt pavement technique, the noise level has been reduced. The sources of noise pollution are the sound produced by the engine, honking by the drivers, and the noise created due to the friction between the tire and pavement surface. In Table 8.5, it is observed that all the roads considered in this study have a higher noise level during the daytime as compared to the night time. In Figure 8.6, it is found that Old Motor Stand Road is the busiest and noisiest road during the day and night. All other roads also cross the desired limit both during the day and at night (ref. Table 8.3). So in this condition, Porous Asphalt Pavement may be a technique to reduce the noise pollution caused by traffic movement.

Table 8.6 Noise level of different categories of vehicles at various speed

Type of vehicle	Speed (km/h)	Noise level [dB(A)] Conventional Asphalt Pavement	Noise level [dB(A)] Porous Asphalt Pavement
Motor cycle	47	71.78	66.57
	42	73.56	69.54
	34	75.12	70.61
	25	76.95	72.40
	20	78.10	73.82
Auto rickshaw	30	75.24	70.68
	25	76.89	72.54
	22	77.15	72.92
	20	77.76	73.51
	15	78.88	74.58
Car	35	75.29	70.99
	30	76.98	72.68
	25	77.58	73.38
	22	78.27	74.02
	18	78.66	74.48
Bus	35	77.82	73.52
	30	78.46	74.14
	25	79.25	74.97
	20	80.02	75.71
	15	81.31	77.01
Truck	35	78.33	74.03
	30	79.21	74.93
	25	80.11	75.83
	20	81.34	76.99
	15	82.56	78.22

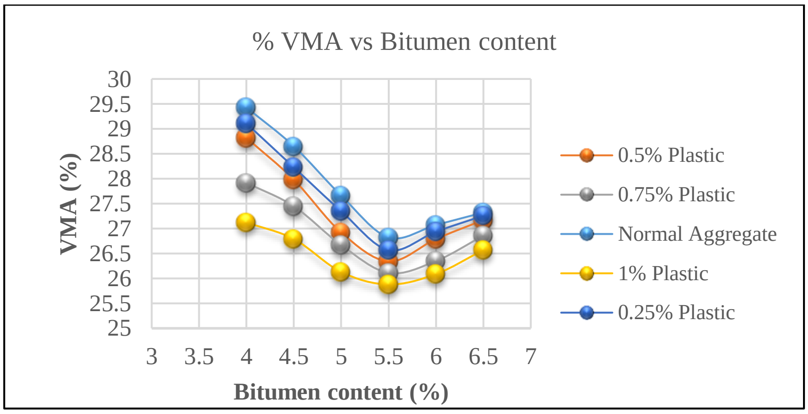


(a)



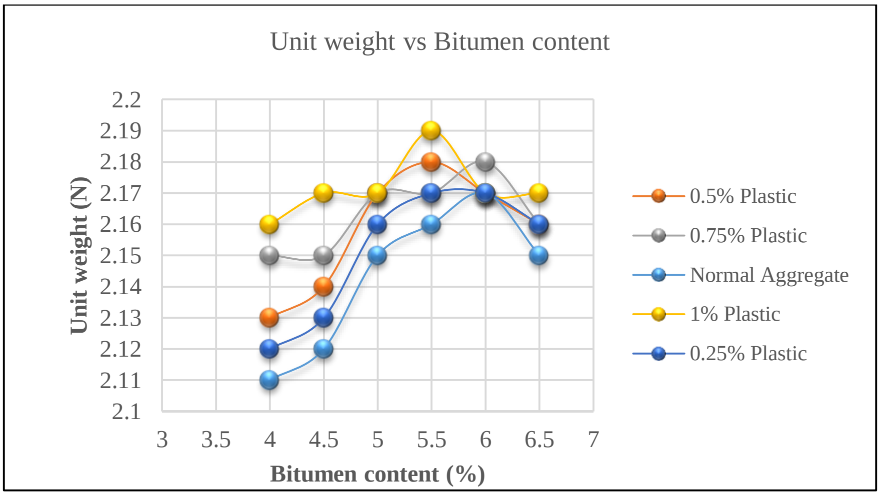
% VFB vs Bitumen content
VFB (%)
48
46
44
42
40
38
36
34
32
30
3
3.5
4
4.5
5
5.5
6
6.5
7
Bitumen content (%)
0.5% Plastic
0.75% Plastic
Normal Aggregate
1% Plastic
0.25% Plastic

(b)



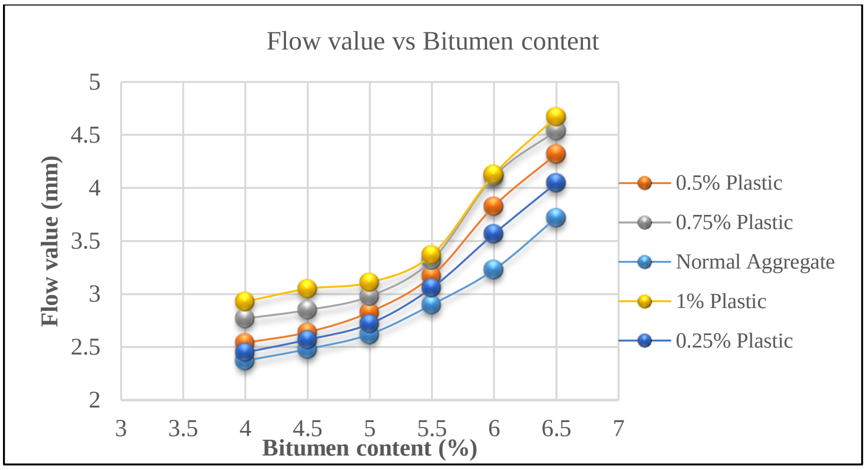
% VMA vs Bitumen content
VMA (%)
30
29.5
29
28.5
28
27.5
27
26.5
26
25.5
25
3
3.5
4
4.5
5
5.5
6
6.5
7
Bitumen content (%)
0.5% Plastic
0.75% Plastic
Normal Aggregate
1% Plastic
0.25% Plastic

(c)



Unit weight vs Bitumen content
Unit weight (N)
2.2
2.19
2.18
2.17
2.16
2.15
2.14
2.13
2.12
2.11
2.1
3
3.5
4
4.5
5
5.5
6
6.5
7
Bitumen content (%)
0.5% Plastic
0.75% Plastic
Normal Aggregate
1% Plastic
0.25% Plastic

(d)



(e)

Figure 8.4 (a) % Air voids, (b) % VMA, (c) Flow value, (d) Unit Weight & (e) VFB% vs Bitumen Content

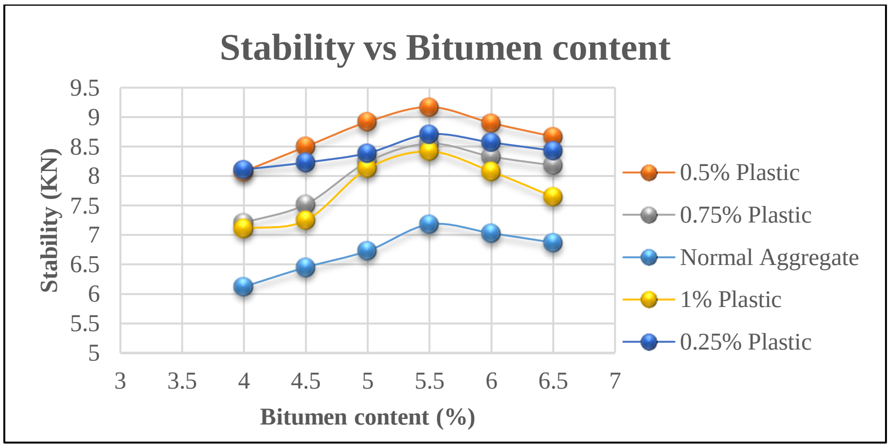


Figure 8.5 Stability vs Bitumen Content

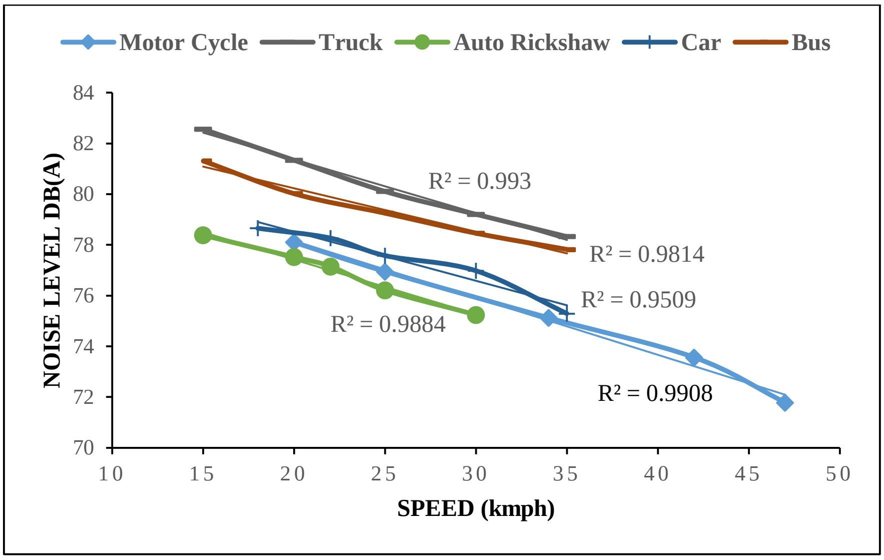


Figure 8.6 Relation between Noise Level and Speed for Conventional Asphalt Pavement

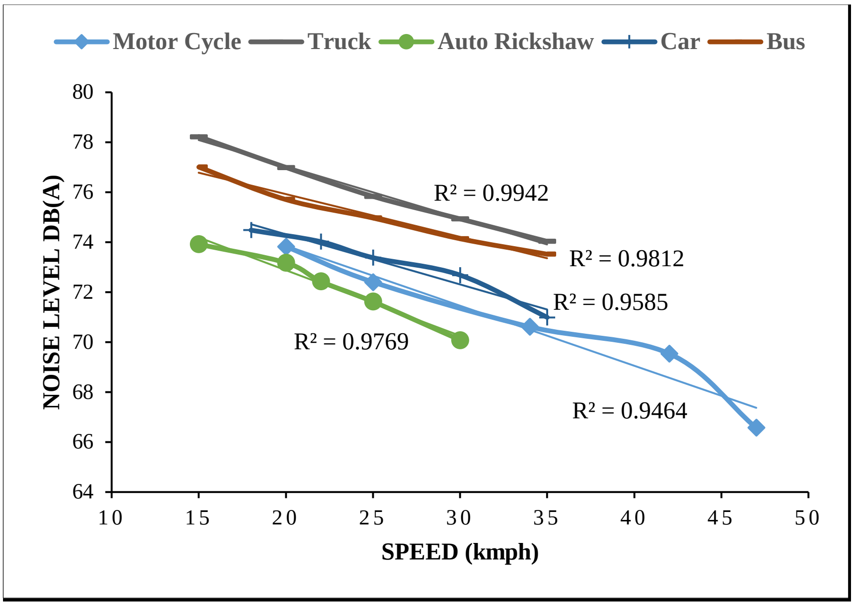


Figure 8.7 Relation between Noise Level and Speed for Porous Asphalt Pavement

Following Regression equations of speed of traffic with noise level are proposed: These equations are proposed based on a noise level study of five categories of vehicles in Agartala city. Equations 1–5 show the correlation between speed and noise level for conventional asphalt pavement, and equations 6–10 show the correlation between speeds and noise level for porous asphalt pavement.

For Conventional Asphalt Pavement the equations are as follows,

Motor Cycle:

$S_L = -0.2241V + 82.633$ ($R^2 = 0.9908$) (1)

Auto rickshaw:

$S_L = -0.2353V + 82.454$ ($R^2 = 0.9797$) (2)

Car:

$S_L = -0.1933V + 82.382$ ($R^2 = 0.9509$) (3)

Bus:

$S_L = -0.1708V + 82.642$ ($R^2 = 0.9814$) (4)

Truck:

$S_L = -0.2118V + 82.605$ ($R^2 = 0.993$) (5)

For Porous Asphalt Pavement the equations are as follows,

Motor Cycle:

$S_L = -0.2399V + 78.65$ ($R^2 = 0.9464$) (6)

Auto rickshaw:

$S_L = -0.2533V + 78.52$ ($R^2 = 0.975$) (7)

Car:

$S_L = -0.2004V + 78.32$ ($R^2 = 0.9585$) (8)

Bus:

$S_L = -0.171V + 79.345$ ($R^2 = 0.9812$) (9)

Truck:

$S_L = -0.2088V + 81.22$ ($R^2 = 0.9942$) (10)

Where,

S_L = Noise Level in dB (A)

V = Speed of Traffic in kmph

From the aforesaid equations, it is observed that the R^2 values are close to 1.00, which indicates that speed and noise level have shown good correlation.

Table 8.7 Traffic noise levels throughout the day and at night in various parts of the city of Agartala for conventional asphalt pavement.

Name of road	Traffic volume (per day)	Noise level dB(A)	
		Day Time	Night Time
Akhaura Road (1)	22055	98.50	88.75
Hari Ganga Basak Road (2)	24560	100.50	89.00
VIP Road (3)	19768	92.50	84.50
Thakur Pally Road (4)	17325	75.50	65.15
Lakshmi Narayan Bari Road (5)	18960	85.20	78.25
Dhaleswar A. A. Road (6)	20343	93.00	87.50
Old Motor Stand Road (7)	25250	101.05	92.10

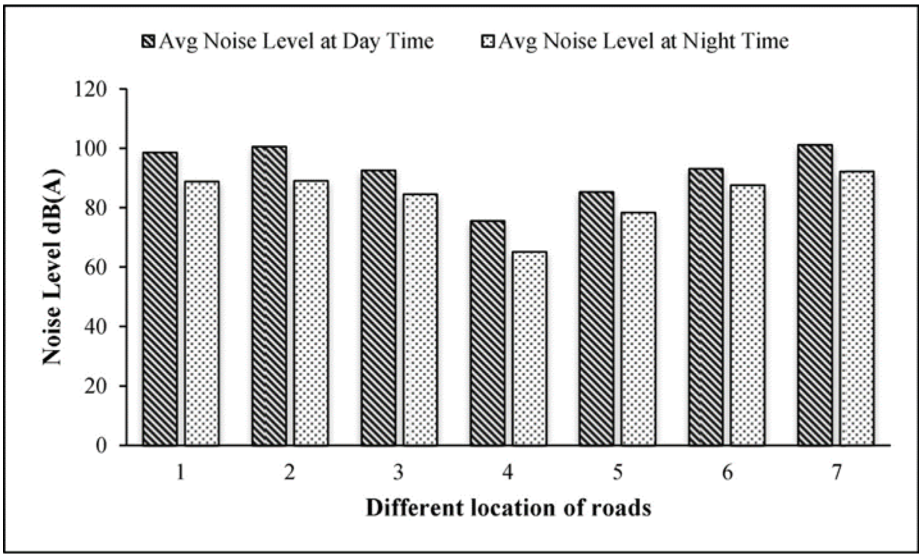


Figure 8.8 Noise Level at 7 different Roads of Agartala City

8.6 Discussion

The amount of vehicle noise is noticeably greater in Agartala. Because of the city's smaller roadways and the near proximity of concrete structures on either side of the roads, the noise that is created is exacerbated. There are more light motor vehicles, including motorcycles, auto rickshaws, and personal automobiles. During peak hours, several areas have frequent traffic bottlenecks. Unnecessary honking by drivers is a major source of noise pollution. Permeable asphalt surfaces can be utilized as an alternative to conventional pavement. The noise level will be lowered if porous asphalt pavement is utilized in place of conventional asphalt pavement. In this study, four different plastic coating percentages—0.25%, 0.5%, 0.75%, and 1%—are applied to stone aggregate. The greatest stability value, 0.5% plastic content, is shown to satisfy the MORTH requirement. Use of Porous Pavement in the road construction is found effective in terms of reduction in noise pollution from the field study (L. Teti et al., 2020).

8.7 Findings of the study

High-occupancy vehicles (HOV), such as large and medium-sized buses and trucks, travel in fewer numbers in Agartala city. But the counts of auto rickshaws, personal cars, and motor cycles are comparatively higher. Due to the lower number of HoVs, the number of small motorized vehicles has increased, which has caused an overall increase in vehicle count. Thus, it has increased the noise pollution in the city. During the daytime, the permissible noise level in commercial areas is 65 dB (A), and at night it is 55 dB (A) (As per Indian Standards). But the average noise level of seven roads in Agartala city has crossed the prescribed level. The noise level can be as high as 95 dB (A) during the daytime, and at night the value can go up to 85 dB (A). This can have adverse effects on both the surrounding environment and human life. It has been shown that noise levels in the pavement can be decreased by 4-5% by employing porous asphalt materials with a 0.5% plastic component overlaid with stone aggregate. Thus, the use of porous asphalt mix on pavement surfaces may be helpful for controlling noise pollution in congested urban areas to some extent.

CHAPTER- 9

EFFECTS OF SHAPE AND SIZE OF COARSE AGGREGATE ON THE POROUS CONCRETE

9.1 General

Permeable concrete is a unique variety of concrete with a notably high level of porosity. Laboratory tests have been performed to determine the impact of coarse aggregate size and shape on the permeability and crushing durability of permeable concrete (PC). In this work, the porous concrete mix's coarse aggregates' flakiness index and angularity number were changed. Porous Concrete can be used in areas where water percolation into the soil does not take place properly. Permeable concrete permits water to percolate into the voids of the concrete, which creates a pathway for rainwater to percolate. The percentage of an aggregate having its least dimension less than 0.6 times the mean dimension is called the flakiness index. It is a crucial parameter since it influences the strength of porous concrete. Angularity is also considered an important property of an aggregate because of its effect on the surface area. The test results show that the crushing strength and permeability are affected by the shape and size of the aggregates. It shows that if coarse aggregate with a high flakiness index is used, then porous concrete exhibits high permeability but less crushing strength. Similarly, porous concrete shows low permeability and greater crushing strength if coarse aggregate with a low flakiness index is used. It can be inferred that if permeability increases, the crushing strength of permeable concrete decreases. It is found that aggregate having an Irregular shape (20 mm) produces the optimum mix at a water-cement ratio of 0.30. In this condition, a proper balance between crushing strength and permeability is attained.

9.2 Introduction

Asphalt pavements are commonly constructed in developing countries like India since they require low initial investment. However, based on their lower life cycle costs than asphalt pavements, cement concrete pavements are the primary mode of transportation in India, according to MORTH. Conventional concrete pavements are not efficient in terms of rainwater management. From an environmental point of view, water may easily percolate through the permeable layers of porous concrete pavement (PCP), which has the capacity to do so. Porous Concrete contributes to reducing noise levels, restoring groundwater, dissipating heat, etc. Porous Concrete Pavement has emerged as a green and sustainable technique for road construction. Many studies are carried out on PCP to get adequate crushing strength and considerable permeability. This type of road is suited for parking lots and low-volume roads since they involve low traffic volumes and can ensure reduced surface runoff through percolation. The gradation of PCP consists of fine aggregates in smaller proportions to maintain higher air voids in the mix. The load-carrying capacity of the mix depends on the structure formed by the coarse aggregate. Various studies have indicated that the overall mechanical properties of the mix are influenced by aggregate properties. The size and shape of aggregates influence the overall effectiveness of porous concrete mixes. The result expressed that irregular and angular shapes of aggregates are favorable shapes. The void content of a porous concrete mixture ranges from 15% to 35%, increasing permeability but decreasing strength. The permeability coefficient of porous concrete is between 0.1 and 5 cm/s, whereas the crushing strength is between 3 and 26 MPa. To get high-strength porous concrete, optimum permeability properties are expected. Despite many studies carried out on the influence of size and shape of aggregates on porous mixes, the behavior of the strength and permeability characteristics of porous concrete needs to be investigated at varying water-cement ratios with different shapes and sizes of aggregates.

In this study, mixes were prepared with flaky, angular, and irregular types of aggregates in different sizes. Two types of W/C ratios, viz. 0.30 and 0.35, are considered for the preparation of porous concrete mixes, and the behavior of the mix is checked in terms of strength and permeability properties.

9.2.1 Permeable Concrete

Permeable concrete is a specific kind of concrete with high porosity that is used to decrease runoff from a site and encourage groundwater recharge (Zhao et al., 2023). Permeable concrete helps water pass through it from rain and other sources. Large particles rather than many or any small aggregates are used to create pervious concrete. The concrete paste is then applied on top of the aggregates, allowing water to pass through the concrete slab as well. Park lots, low-traffic zones, residential streets, footpaths, and conservatories typically use existing concrete. It is a crucial element of ecologically friendly building and one of several little-effect development techniques employed by developers to safeguard water quality.

When pervious concrete is utilized as pavers, rainwater may be swiftly absorbed at a rate of 3 to 5 gallons/mnt/sq. ft. across the surface area, which is quicker than the rate of flow necessary to stop runoff in the majority of rain events. Storm water can be held in a layer of coarse stone beneath the pavement or allowed to soak into the subsurface soil.

Impermeable pavements frequently result in greater amounts of contaminated runoff, although the pavement itself serves as a holding place to reduce this. The process of filtering aids in the water's purification. Aerobic microorganisms in the spaces between open pavement cells assist in the breakdown of toxic substances and pollutants when water penetrates through the pavement.

9.2.2 Benefits of Porous Concrete

Both environmentally friendly and economically, porous concrete is advantageous. The advantages are covered below.

9.2.3 Environmental Benefits

- Lessen the quantity of runoff that enters storm sewers without being treated.
- Recharge groundwater directly to keep aquifer levels stable.
- Direct more water towards landscaping and tree roots to reduce the need for irrigation.
- Reducing pollutants that endanger delicate ecosystems and taint watersheds.
- Get rid of sealants and asphalt pavements' hydrocarbon emissions.

9.2.4 Economical Benefits

- The Centre for watershed protection claims that little effect water runoff management methods such as permeable concrete may be installed for two to three times less money than traditional curbs, gutters, storm drain inlets, pipework, and retention basins.
- Since pervious concrete projects often do not require storm sewer ties-ins, there is no need to spend money on storm drains and underground piping. Municipalities might not need to expand their current storm sewer networks as much if they use pervious concrete to support new residential and commercial construction.
- There is no need to buy more property to create massive ponds for retention and other water-retention and filtering systems because permeable concrete surface serves as both a surface and a stormwater management system.
- Paving made of pervious concrete is environmentally friendly and has a similar lifespan to conventional concrete.

9.2.5 History of Porous Concrete

- The initial applications of pervious concrete were for load-bearing walls and pavement topping in Europe. The 1800s saw this occur.

- Cost effectiveness was achieved since less cement was utilized than in typical concrete. This was the primary driver behind the development of pervious concrete.
- It briefly gained favor for 2-story structures in Scotland and England in the 1920s. Due of the lack of cement after World War II, pervious concrete became a fully-fledged industry.
- It gained widespread acceptance in the United States during the 1970s as well. In contrast, it wasn't introduced till the 2000s in India.

9.2.6 Design of Porous Concrete

The design for applying porous concrete consists of a minimum of three layers: two to four inches of porous concrete, one to two inches of filter material made of 0.5-inch crushed aggregate, twelve inches of minimal reservoir material composed of one to three-inch aggregate, and an additional layer of filter fabric. A mixture of Portland cement, water, and regular open-graded coarse aggregate makes up porous concrete. In contrast to ordinary concrete's 3 to 5% void space, which varies from 15% to 22% in porous concrete. The concrete itself offers some runoff pre-treatment. Some contaminants are removed with the help of the crushed aggregate filter layer. The water reservoir bed is a thin, open-graded, clean-washed layer of aggregate with at least 40% void area, and serves as a storage area for runoff. The filtered runoff subsequently seeps into the groundwater source through the uncompacted soil base. Using forms, porous concrete is poured and then leveled with a screed. Both jointing and finishing are not necessary. Don't overwork the surface, please. Porous concrete is appropriate for a variety of light-duty applications, including overflow parking spots, residential roadway parking lanes, parking lots, and evacuation lanes. If properly maintained, permeable concrete can have a baseline service life of 20 years. This maintenance includes frequent surface sweeping to prevent silt buildup and clogging.

When enough paste is used to cover and bind the aggregate particles together, a network of swiftly draining, extremely porous gaps is formed. In comparison to ordinary concrete, strength is decreased by both the low mortar content and the high porosity, although sufficient strength may still be easily attained for many applications.

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9.2.7 Objective of Present Study

The objectives of present study are as follows;

- To study on the crushing strength of permeable concrete with varying shape and size of aggregates.
- To check the permeable characteristics of porous concrete having variation in shape and size of coarse aggregates.
- To determine the change in strength of porous concrete at different water-cement ratios.
- To find the optimum gradation of coarse aggregate, which will provide best performance in terms of strength and permeability on porous concrete.

9.3. Materials and Methodology

9.3.1 Cement

Ordinary Portland cement 43 (OPC 43) grade has been used in this experimental work conforming to IS 8112 (BIS 1989). The following properties were checked for the cement as mentioned in Table 9.1.

Table 9.1 Different test results of Cement properties

Fineness (%)	Standard Consistency (%)	Specific Gravity	Crushing Strength (MPa)	Setting Time (Initial) (In min)	Setting Time (Final) (In min)
5.2	30	3.12	38.5	92	433

Table 9.2 Chemical Compositions of Cement

Chemical Constituent	**SO_3**	**NaO**	**LOI**	**Fe_2O_3**	**MgO**	**SiO_2**	**Al_2O_3**	**CaO**
Cement	3.9	0.78	2.55	2.32	2.55	19.85	4.87	62.75

9.3.2 Coarse Aggregate

We employed three different kinds of coarse aggregates. The aggregates were categorised as flaky, angular, and irregular according to IS: 2386 (Part-I) 1963 based on their shape features. To divide the test samples into fractions of a single size, sieving was used. Granite (a coarse-grained intrusive igneous rock) has been added as a coarse aggregate in the current research. Table 9.3 displays the coarse aggregate's characteristics.

Table 9.3 Different test results of Coarse Aggregate

Shape	**Flakiness Index (%)**	**Aggregate Type**	**Specific Gravity**	**Water Absorption (%)**	**Abrasion Value (%)**	**Crushing Value (%)**	**Impact Value (%)**	**Bulk Density (kg/m^3)**
Small thickness	40	Flaky	2.82	1.95	21.08	12.82	13.93	1750
Well defined Edges	18	Angular	2.80	1.79	16.52	10.86	11.35	1650
Rounded edges	10	Irregular	2.79	1.51	12.45	8.81	7.54	1620

9.3.3 Water

Fresh water has been used in the preparation of porous concrete. After its preparation the mix has been cured regularly. Any form of chemical admixtures are not used in the mixes because the objective of the work is to determine the impact of the angularity of the aggregate and water-cement ratio.

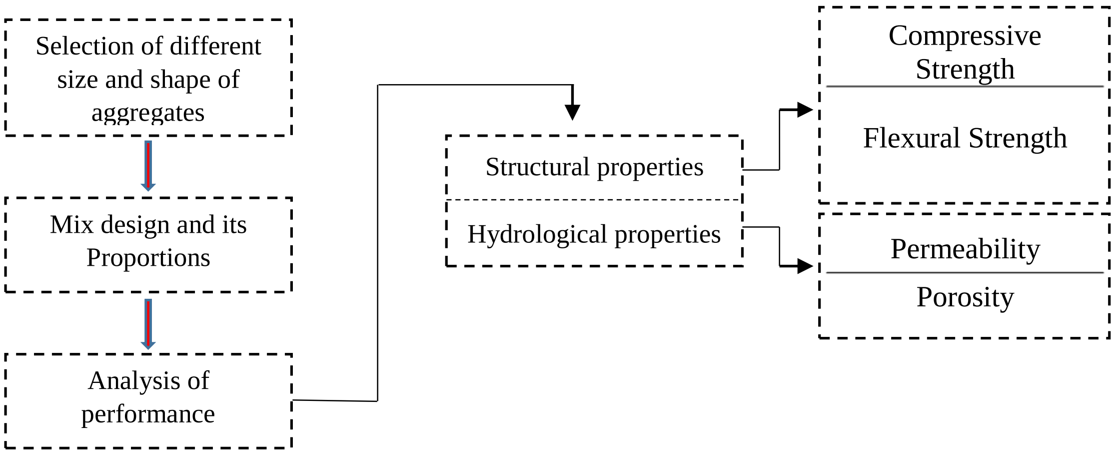


Figure 9.1 Block diagram of the methodology in the study

9.3.4 Mix Proportioning:

The mix proportioning method complies with the requirements of ACI 522R-10 and IS 10262:2019 and is based on the absolute volume concept. Next, the necessary void volume is assessed. Deducting the volume of paste and the volume of voids from the unit volume of concrete yields the total volume of aggregate. The volumes of the fine and coarse aggregates are then chosen. For each mix, a constant void of 15% is chosen. In this study, three types of coarse aggregates have been used that are size- and shape-wise different, as shown in Table 9.3. Different properties of three types of coarse aggregates have also been determined, as shown in Table 9.3. For each category of shape of coarse aggregate, three (3) types of ranges of size have been considered, as shown in Table 9.4. Samples have been prepared for each category of size and shape at the W/C ratios of 0.30 and 0.35. Different identification numbers have been assigned to the different mixes in such a way that the first letter highlights the type of aggregate [Flaky (F), Angular (A), or Irregular (I)]. The aggregates have been tested for several properties by taking three samples of different shapes and sizes at a time (as shown in Table 9.4).

Table 9.4 Classification of coarse aggregates

Description	Containing Size (mm)	Classified as
Aggregates have a smaller thickness as compared to other dimensions	20-16 16-12.5 12.5-6.3	Flaky (F)
Aggregates having well-defined edges	20-16 16-12.5 12.5-6.3	Angular (A)
Aggregates having rounded edges	20-16 16-12.5 12.5-6.3	Irregular (I)

Table 9.5 Specimen names for various porous concrete samples

Aggregate Type	Aggregate Size	W/C Ratio	Sample Name
F	20-16	0.30	F-20-0.30
F	16-12.5	0.30	F-16-0.30
F	12.5-6.3	0.30	F-12.5-0.30
F	20-16	0.35	F-20-0.35
F	16-12.5	0.35	F-16-0.35
F	12.5-6.3	0.35	F-12.5-0.35
A	20-16	0.30	A-20-0.30
A	16-12.5	0.30	A-16-0.30
A	12.5-6.3	0.30	A-12.5-0.30
A	20-16	0.35	A-20-0.35
A	16-12.5	0.35	A-16-0.35
A	12.5-6.3	0.35	A-12.5-0.35
I	20-16	0.30	I-20-0.30
I	16-12.5	0.30	I-16-0.30
I	12.5-6.3	0.30	I-12.5-0.30
I	20-16	0.35	I-20-0.35

I	16-12.5	0.35	I-16-0.35
I	12.5-6.3	0.35	I-12.5-0.35

9.3.2 Tests on concrete

- **Compressive Strength Test**

The test for crushing strength is necessary for porous concrete because it measures the hardness of concrete which is a very important attribute. The compression testing apparatus is used to conduct this test (CTM). 15 cm x 15 cm x 15 cm porous concrete specimens are used for this test, and the findings are assessed after 7 and 28 days, respectively.

Figure 9.2 Crushing Strength Test Machine

- **Flexural Strength Test**

Flexural strength is the ability of a concrete beam to resist breaking when bent. Concrete beams 50 cm long are loaded during testing to determine their strength. An experiment with four loading points is used for this test. During the four-point loading test, forces are applied to the four various locations. Five centimetres from the ends, the beam is supported at two locations below. Typically, the dimensions are 15 × 15 × 70 cm.

- **Permeability Test**

In this work, the permeability of several permeable concrete specimens is determined using the permeability test (Constant head method). Knowing the discharge in the tube, the permeability can easily be calculated by using the following formula;

$$K = \frac{Q \times l}{A \times h}$$

Where,
Q = Discharge (in mm^3/sec)
A = Area of Cross-section (in mm^2)

l = Specimen's length (in mm)
h = Height of constant head (in mm)
K = Coefficient of permeability (in mm/hr)

Figure 9.3 Permeability Test Apparatus

- **Porosity:**

A cylindrical specimen with a 100-millimeter diameter and 200 millimetres height was subjected to the ASTM D 1754 water displacement method test to determine its porosity. By calculating the difference between the dry and submerged weights, the porosity was determined. The samples were then permitted at least 24 hours to dry in the thermostatically controlled 110 °C oven after being fully cured underwater, their submerged weights being recorded. The formula below was used to compute the porosity property.

$$\phi = \left[1 - \frac{(A - B)}{\rho_w \times D^2 \times L}\right] \times 100$$

Where,

ρ_w = Water density, A = Specimen's dry weight, B = Specimen's submerged weight, L = Specimen's length, D = Specimen's average diameter, Ø = Porosity of the mix

9.4. Results and Discussions:

Various tests like the compression resistance test, the flexural strength test, the permeability test, and the porosity test have been performed on the specimens of permeable concrete. Tests on porous concrete have been performed by varying the aggregate size, flakiness index, and w/c ratio. All tests have shown the influence of varying size and shape aggregates on the samples after a 7days, and 28 days curing period.

Table 9.6 Crushing strength results on porous concrete containing w/c ratios of 0.30 and 0.35 after 7 days of curing

Sample Name	**Crushing strength (MPa)**	
	Water-Cement ratio - 0.30	**Water-Cement ratio- 0.35**
F-20	14.11	14.12
F-16	17.56	14.38
F-12.5	16.92	16.90
A-20	14.95	17.72
A-16	14.37	16.93
A-12.5	15.27	14.40
I-20	20.40	19.67
I-16	19.58	19.98
I-12.5	18.39	19.12

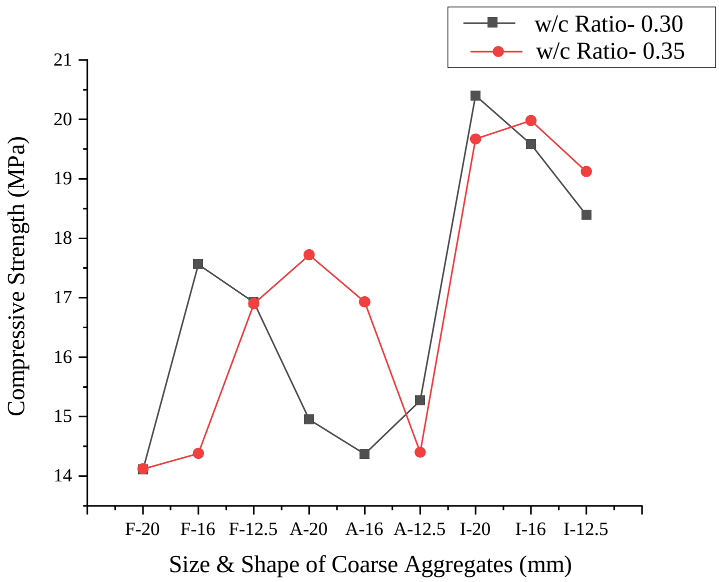


Figure 9.4 Size & Shape of Coarse Aggregates vs Crushing Strength at w/c Ratios of 0.30 and 0.35 after 7 days curing

A crushing strength test has been done on the samples at Water-Cement ratios of 0.30 and 0.35 after 7 days of curing, as shown in Table 9.6. The results are plotted as shown in Figure 1. In the figure, it is observed that after 7 days, the crushing strength is maximum for the sample 1–20 with a w/c ratio of 0.30, and the least strength is obtained in the sample F–20 with a W/C ratio of 0.30.

Table 9.7 Results of Flexural Strength test on porous concrete with water-cement ratio 0.30 and 0.35 after 7 days curing

Sample Name	Flexural Strength (MPa)	
	Water-Cement ratio - 0.30	Water-Cement ratio- 0.35
F-20	2.29	2.28
F-16	2.41	2.32
F-12.5	2.39	2.38
A-20	2.33	2.43
A-16	2.31	2.39
A-12.5	2.35	2.32
I-20	2.71	2.65
I-16	2.64	2.67
I-12.5	2.48	2.61

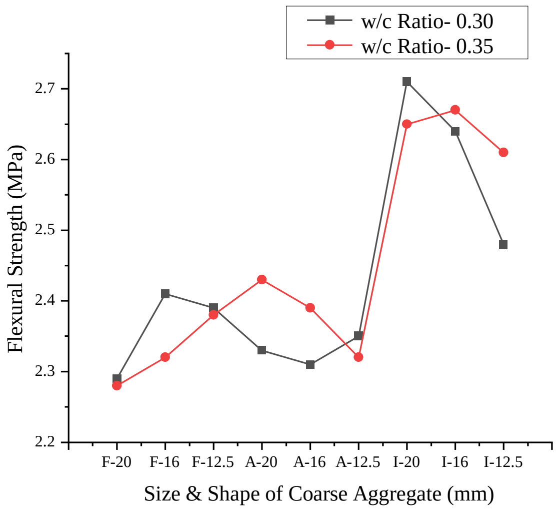


Figure 9.5 Size & Shape of Coarse Aggregates vs Flexural Strength at w/c Ratios of 0.30 and 0.35 after 7 days curing

A flexural strength test has been performed on the samples at Water-Cement ratios of 0.30 and 0.35 after 7 days of curing, as shown in Table 9.7. The results are plotted and represented graphically, as shown in Figure 9.2. The figure shows that sample I-20 achieves its greatest flexural strength at a w/c ratio of 0.30, while sample 20 achieves its lowest value at a w/c ratio of 0.35.

Table 9.8 Results of porous concrete with Water-Cement ratio 0.30 after 28 days curing

Sample Name	Crushing strength (MPa)	Flexural Strength (MPa)	Porosity (%)	Permeability (cm/s)
F-20	18.61	2.34	27.09	2.39
F-16	20.63	2.52	24.87	2.26
F-12.5	22.17	2.58	24.49	2.23
A-20	24.87	2.64	21.43	1.95
A-16	25.13	2.94	19.63	1.78
A-12.5	26.84	3.11	19.32	1.71
I-20	29.54	3.85	16.75	1.51
I-16	28.94	3.71	17.23	1.56
I-12.5	28.32	3.62	17.45	1.60

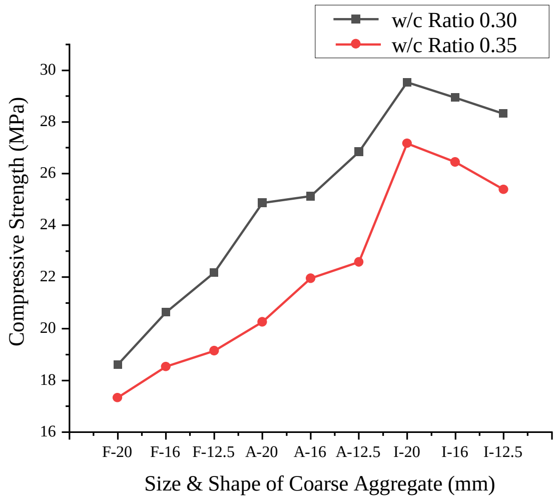


Figure 9.6 Size & Shape of Coarse Aggregates vs Crushing Strength at w/c Ratios of 0.30 and 0.35 after 28-days curing

Table 9.9 Results of porous concrete with water-cement ratio 0.35 after 28 days curing

Sample Name	Crushing strength (MPa)	Flexural Strength (MPa)	Porosity (%)	Permeability (cm/s)
F-20	17.33	2.28	28.47	2.45
F-16	18.53	2.32	27.31	2.41
F-12.5	19.14	2.35	26.69	2.35
A-20	20.26	2.47	24.33	2.31
A-16	21.95	2.55	23.91	2.29
A-12.5	22.58	2.58	22.11	2.19
I-20	27.17	3.27	17.63	1.67
I-16	26.45	2.99	21.93	1.88
I-12.5	25.39	2.84	19.87	1.74

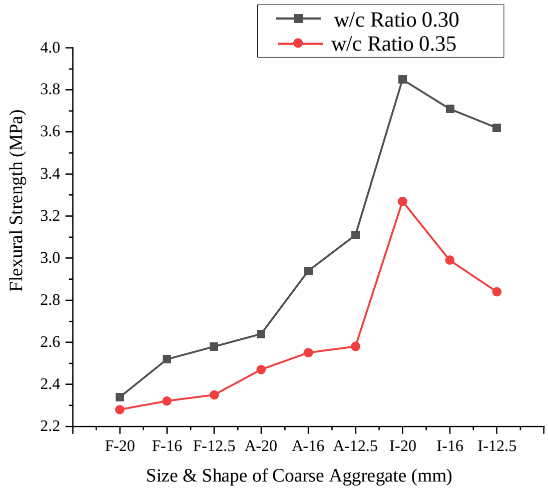


Figure 9.7 After 28 days of curing, the size and shape of coarse aggregates were compared to their flexural strength using w/c ratios of 0.30 and 0.35.

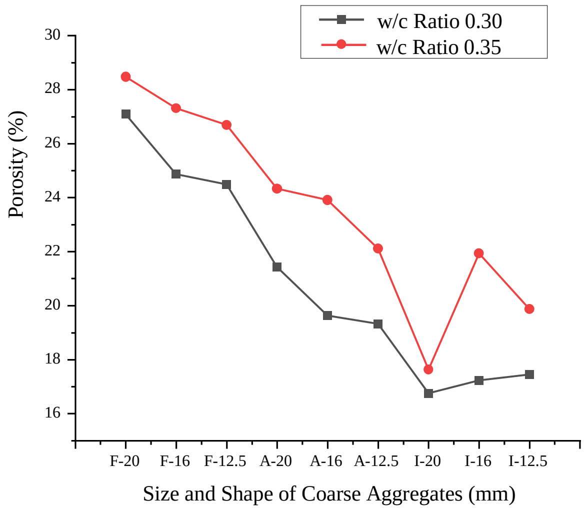


Figure 9.8 Size & Shape of Coarse Aggregates vs Porosity using w/c Ratios of 0.30 & 0.35 after 28 days curing

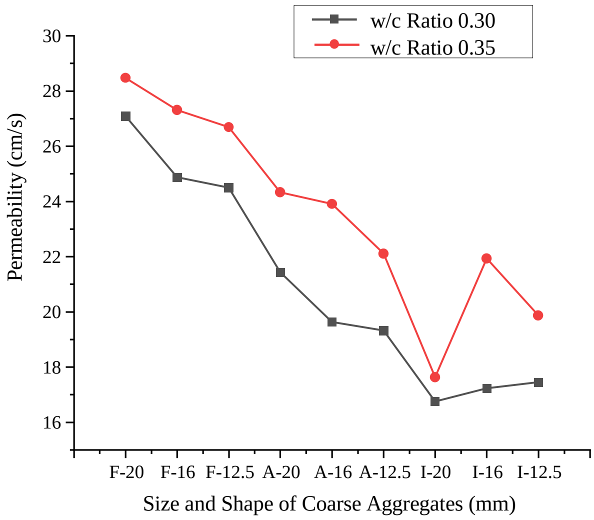


Figure 9.9 Size & Shape of Coarse Aggregates vs Permeability using w/c Ratios of 0.30 & 0.35 after 28 days curing

Different test results are tabulated in Tables 9.8 and 9.9 for w/c ratios of 0.30 and 0.35. Test results are also plotted and represented graphically, as shown in Figures 9.3, 9.4, 9.5, and 9.6. From Figure 9.3, it is noticed that samples 1–20 show the maximum Crushing strength value at Water-Cement ratios of 0.30 and 0.35, but the maximum value is obtained for w/c ratio 0.30 for the same sample. In Figure 9.4, the maximum Flexural strength value is obtained for samples 1–20 at w/c ratios 0.30 and 0.35, but the maximum test result is observed at w/c ratio 0.30. Figures 9.5 and 6 represent the test results of porosity and permeability, respectively, where it is evident that both crushing and flexural strength vary inversely with porosity and permeability. Different shape and size of coarse aggregate has different influence on the porous mix. Irregular shape of aggregate is found suitable in terms of strength to be used in the mix (K. Ćosić et al., 2015).

9.5. Findings of the study

In this study, different shapes and sizes of coarse aggregates, like flaky, angular, and irregular, are used for the sample preparation. Mixes have been cast at two types of water-cement ratios, viz., 0.30 and 0.35. Various tests like crushing strength, flexural strength, porosity, and permeability have been carried out on the mix samples.

From the results, it is noticed that for flexural strength and crushing tests, the maximum value is gained in the sample I-20, i.e., the irregular shape of aggregate for both 0.30 and 0.35 water-cement ratios after 7 days of curing among all types of mixes. It is also noticed that the results obtained for crushing and flexural strength tests after 28 days of curing are found to be the maximum for sample I-20 at both water-cement ratios among all types of samples.

Although the result of porosity and permeability for sample I-20 is lower as compared to other samples, it is within the permissible range as per IRC 44-2017. It is evident that the crushing and flexural strength of the sample are inversely related to the mixture's porosity. It may be determined from the observations that the use of irregular shapes of aggregates having a size of 20 mm improves the different strength parameters of the mix, but properties like permeability and porosity are decreased.

This study can be extended in the future by adding some materials to improve the strength parameters. An investigation may be performed at the microscopic level to check the internal behavior of the mix.

CHAPTER- 10

ENERGY HARVESTING FROM PEDESTRIAN MOVEMENT USING PIEZOELECTRIC MATERIAL

10.1 GENERAL

The quantitative element required to complete a variety of mechanical, physical, and other tasks is energy. The most important type of energy, electrical energy, is typically produced using natural resources. Electricity is produced by large power plants, which are expensive to construct. Because fossil fuels like coal, oil, and gas are used to produce electricity, there are fewer natural resources available. On the other hand, it pollutes the environment. In order to address the worldwide electricity crisis, researchers are looking for creative ways to produce more electricity from many alternative materials without upsetting the delicate balance of nature. Numerous studies have shown that hydroelectric, solar, and wind energy can produce power in place of fossil fuels. Benefits are provided by the piezoelectric energy harvesting method. Due to its ease of installation and safety, this power-generating technology has garnered significant interest over the past ten years. The degree to which piezoelectric crystal materials are bent determines how much energy can be collected from them. The stored energy may cause the system's efficiency to increase (Alaei. Z, 2016) Energy harvesting, also known as energy storage technology, is the process of gathering, storing, and distributing surplus energy for use in human activities. Energy harvesting devices that use transduction have lately made significant progress in addressing the world's ever-growing energy needs (Calio et al., 2014).

Electrostatic, electromagnetic, and piezoelectric techniques are employed for energy harvesting. Piezoelectric transduction is the most promising technique for energy harvesting. Since no by-products are produced, the technique is advantageous for the environment. Mechanical dampening and the quantity of power generated by piezo crystals are inversely related. In this study, piezo crystals are sandwiched between two rubber strips because of their low damping. The goal of this project is to collect energy by walking on rubber or piezo-embedded walkways.

10.2 OBJECTIVE OF THE STUDY

The major goal of the chapter is to use piezoelectric material to generate power by applying pressure from foot traffic to the walkway. A device to gather the energy generated by tread will be placed on the sidewalk. A route is the subject of a study to produce electricity in an unusual way. In order to use the electricity created by this method to power LED lights, recharge mobile devices, and power other equipment, these piezo crystals have been covered in rubber strips and set on the pavement. In this study, piezo units with or without rubber are employed to harvest energy from pedestrian movement using piezo crystals sandwiched between rubber strips due to their low damping.

10.3 PROPERTIES OF PIEZOELECTRIC

10.3.1 Piezoelectric theory

In 1880, Pierre and Jacques, two brothers, discovered the piezoelectric effect, which explains how a particular crystal generates electricity when subjected to mechanical stress. These things are referred to as piezoelectric materials. Greek origins can be found in the word "piezoelectricity," as we use it now. In this usage, "piezein" refers to pushing or squeezing. These substances behave like stable crystals when no outside pressure is present. Two sorts of piezoelectric phenomena are routinely used to generate electricity: direct effects and converse effects. The applied pressures directly induce polarization by changing the gaps between the +ve and -ve charges in the crystal, which is how electricity is produced. The elastic strain, on the other hand, has been brought on by the external forces operating on the crystal because these crystal dimensions change. The electricity in this case is produced by crystal deformation. Piezoelectric technology has been used in many different contexts, such as in the manufacture of combustion engines, as a quality control tool, and as a backup power source. It has been demonstrated that this technique provides the service without causing any pollution.

Today, electricity is crucial for us to complete our everyday responsibilities. Processing our daily duties would be quite challenging without power. Fossil fuels are used to generate power, which causes enormous pollution and endangers human life. Curiosity is piqued by the rate at which fuel supplies are running out, so efforts are being made to find some extra practical ideas for generating electric energy. This proposal focuses on employing sidewalks with human tread made of rubber or piezo as a source of energy. The process is shown in Figure 10.1.

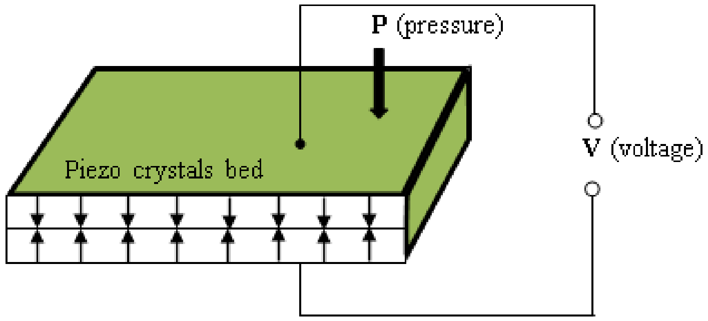


Figure 10.1 Basic Piezoelectric Diagram

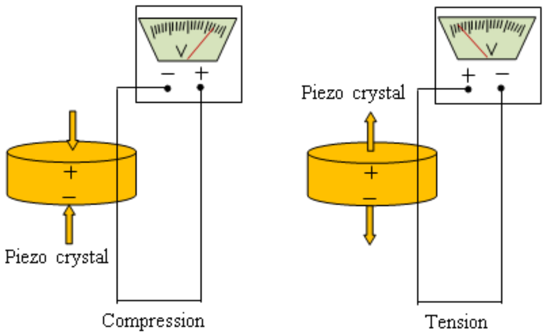


Figure 10.2 Piezoelectric Crystal Behavior under External Forces

10.3.2 Methodology for Pedestrian Energy Harvesting

Piezoelectric materials have an inherent ability to produce electrical potential when compressed, expanded, or mechanically changed. Piezo crystals of a 25-mm diameter are used in this work to generate the voltage. Currently, work is being done to harvest energy by walking on a route with or without rubber strips that contain piezo components. Both parallel and series connections are made between the eight piezo crystal plates. In this case, four plates are connected in series to increase voltage, while two parallel sets are produced to increase current. The test is conducted under two different conditions, such as when the piezo crystals are attached to rubber strips and when they are not. Rubber strips with piezo implanted in them are used to lessen mechanical damping so that more power can be obtained.

10.3.3 Study area

The investigation was carried out in various areas of the Indian city of Agartala. There are roughly 5 lakh people living in the city. All of the places were chosen in the CBD (Central Business District) section of Agartala city, which is constantly congested. These areas include Post office chowmuhani (L1), Math chowmuhani (L2), Kaman chowmuhani (L3), Motor stand chowmuhani

(L4), Paradise chowmuhani (L5), and RMS chowmuhani (L6). As a result, individuals are using the pathways to get where they need to go. Every area had a 15-day pedestrian survey from 6 AM to 10 PM, and the number of pedestrians belonging to each weight category was noted. The average number of pedestrians are observed at different locations presented in Table 10.1.

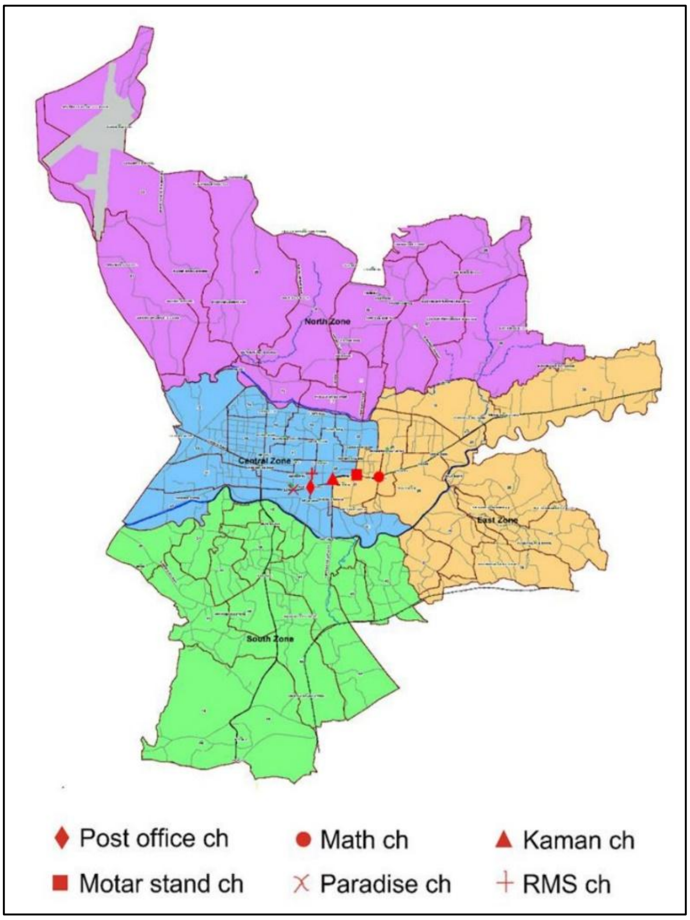


Figure 10.3 Agartala Map Showing Different Study Locations in CBD

10.3.4 Material requirements

In this work, piezo crystal materials with a 25-mm diameter are used to generate electricity. The characteristics of piezo crystals are shown in Table 10.3. The rectifier converts the alternating current (AC) produced by the piezo crystal into direct current (DC), which can subsequently be used to charge mobile devices and illuminate the roadside at night with LED lights. Diodes are semiconductor parts used in rectifier circuit construction. DC power can be produced and stored using super capacitors, which have a higher charge-delivery rate than rechargeable batteries. The maximum output power and mechanical damping are inversely related. Rubber strips are used to wrap piezo crystals because of their low damping.

10.3.5 Modelling of piezo electric harvester

The frame is assumed to vibrate as y (t) and z (t) in response to an external vibration, which is referred to as mass motion. The mass's movement will cause the transducer to distort, transforming mechanical energy into electrical energy. In order to generate electromechanical feedback and further electrical damping, the transducer applies a restoring force (Fe) to the mass (Roundy and Wright, 2004). Electricity will be created as a result of the masses struggle against the restoring force. It is feasible to model the second-order mass-spring-damper (m-k-d) system as the piezoelectric kinetic energy harvester.

The force balance equation of piezo harvester can be written as:

$$ma = \frac{md^2z}{dt^2} + d\frac{dz}{dt} + kz + F_e \tag{1}$$

Where a is acceleration on the harvester frame.

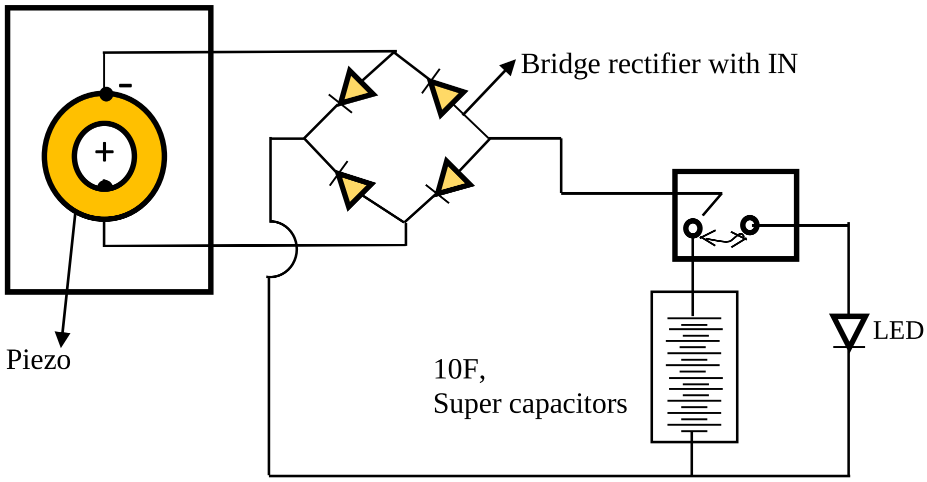


Figure 10.4 Circuit diagram of the system.

Table 10. 1. Geographic Positions of Study Locations in CBD Area of Agartala City

Location	Latitude	Longitude
Post office ch. (L1)	23.82942	91.27859
Math ch. (L2)	23.83113	91.29089
Kaman ch. (L3)	23.83094	91.28263
Motar stand ch. (L4)	23.83145	91.28684
Paradise ch. (L5)	23.82884	91.27533
RMS ch. (L6)	23.83191	91.27874

Table 10. 2 The Average Number of Pedestrians at Various Locations of Agartala City

Location	No of pedestrians corresponding to the person weight (kg)									Total
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	>90	
L1	108	193	324	620	837	1554	1356	521	312	5825
L2	80	138	226	789	742	1279	1103	535	395	5287
L3	67	124	198	545	953	1173	1067	469	369	4965
L4	84	186	256	551	657	1125	937	365	234	4395
L5	71	146	169	348	563	928	921	301	183	3630
L6	95	151	123	253	625	880	764	224	165	3280

Table 10.3 Characteristics of piezo crystal.

Property	Values
Outer diameter	25 mm
Thickness	1 mm
Resonant Frequency (thickness)	2110 kHz
Resonant Frequency (radial)	91 kHZ
Electrical capacitance	5.362 nF
Piezo material	PIC181

$$a = \frac{d^2 y}{dt^2}$$

If the restoring force is considered as a damping force. i.e. $F_e = d_e \frac{dz}{dt}$

The equation can be rewritten as

$$ma = \frac{md^2 z}{dt^2} + d\frac{dz}{dt} + kz + d_e \frac{dz}{dt}$$

Taking Laplace transform;

$$ms^2 y = ms^2 z + (d + d_e)sz + kz$$

$$ms^2 y = \left[s^2 + \left(\frac{d + d_e}{m} \right) s + \frac{k}{m} \right] mz$$

$$\frac{Z(s)}{Y(s)} = \frac{s^2}{s^2 + \left(\frac{d + d_e}{m} \right) s + \frac{k}{m}} = \frac{S^2}{s^2 + 2\omega_n (\zeta_d + \zeta_e) + \omega_n^2} \quad (2)$$

Where, $\zeta_d = \dfrac{d}{2m\omega_n}$; $\zeta_e = \dfrac{d_e}{2m\omega_n}$ and $\omega_n = \sqrt{\dfrac{k}{m}}$

From equation 2, it can be derived as

$$Z(\omega) = \frac{\dfrac{\omega}{\omega_n} y}{\sqrt{\left[1-\left(\dfrac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_d+\zeta_e)\dfrac{\omega}{\omega_n}\right]^2}} \qquad (3)$$

Considering $I \cong Z$ and $V \cong F$

$$P(\omega) = \frac{Z.^2}{2} d_e = \frac{(\omega Z)^2}{2} d_e$$

$$P(\omega) = \frac{\omega^2}{2}\zeta_e (2m)\omega_n \frac{\left(\dfrac{\omega}{\omega_n}\right)^2 y^2}{\left[1-\left(\dfrac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_d+\zeta_e)\dfrac{\omega}{\omega_n}\right]^2}$$

$$P(\omega) = \frac{m\left(\dfrac{\omega}{\omega_n}\right)^3 \omega^3 y^2 \zeta_e}{\left[1-\left(\dfrac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_d+\zeta_e)\dfrac{\omega}{\omega_n}\right]^2}$$

At resonance condition $\omega = \omega_n$

$$P(\omega) = \frac{m\omega^3 y^2 \zeta_e}{4(\zeta_d+\zeta_e)^2}$$

So the power dissipated will be maximum when $\zeta_d = \zeta_e$

$$P(\omega) = \frac{m\omega^3 y^2}{16\zeta_d}$$

Putting, $\zeta_d = \dfrac{d}{2m\omega_d}$ and $a = \omega^2 y = \omega_n{}^2 y$

$$P_{\max} = \frac{(ma)^2}{8d} \qquad (4)$$

Where, P_{max} is maximum output power proportional to 1/d, so mechanical damping is kept low to get large power.

10.3.5. PEDESTRIAN MOVEMENT

10.3.5.1. Case 1: Piezo crystals without rubber strips

Eight piezo crystals are initially installed on the wooden frame, as illustrated in Figure 10.5(a). The piezo crystals are connected in two parallel sets, and each set is connected by four plates in series. The series connection used to connect the plates raises the voltage level. These piezo crystals are covered with synthetic sponge and taped to keep them in place, as shown in Figure 10.5 (b). On top of these crystals is a wooden frame that measures 24 by 13 cm. The complete arrangement is shown in Figure 10.5 (c).

10.3.5.2. Case 2: Piezo embedded rubber strips

Analysis shows that maximum output power and mechanical damping have an inverse connection [Equation (4)]. In this situation, rubber strips are used to produce low damping. In this case, rubber strips that are 3 cm long, 3 cm wide, and 0.1 cm thick are implanted in the piezo crystals. These rubber strips with piezo inserts are located between the bottom and top wooden frames. A total of eight piezo crystals are connected via two parallel sets of four plates each. Both times, various human weights moving sporadically over a configuration of piezo crystals at speeds of 3 kmph (slower speed) and 5 kmph (normal speed) are employed. The corresponding voltages are measured after 800 repeats.

Piezo crystals are organized in two different ways in the lab, as shown in Figure 10.6: Series-Parallel Combination (SPC) and Parallel-Series Combination (PSC). It has been discovered that SPC produces better results than PSC. The test outcomes for instances 1 and 2 are listed in Tables 10.4 and 10.5. In both SPC and PSC scenarios, the results from the piezo-embedded rubber strips are superior to those from the piezo-sans rubber strips. According to the results, rubber strips added to piezoelectric materials produce voltages of 13.32 V and 10.31 V at normal speed and lower speed at 90 kg of weight on SPC, respectively.

In a manner similar to this, piezoelectric materials without rubber strips generate voltages of 10.77 V and 8.19 V, respectively, which correlate to faster and slower speeds at 90 kg of weight on SPC. The extraordinary robustness of rubber strips, which recover piezo crystal distortion after the weight of pedestrians has been removed, is mostly to blame for this. Piezo crystals with high recoverable deformation yield superior output voltages for repeated repetitions.

It is also clear that the output voltage increases with walking speed and applied pressure. The output voltage change for case 2 with pressure is shown in Figure 10.8 for both faster and slower speeds. The relationship between the generated voltage and the applied pressure is nonlinear. The best-fit

Equations and R^2 values are shown in the respective figures. It reveals that there are consistently significant correlations between the voltage and pressure output (R^2 values > 0.98).

10.3.6. Sensitivity analysis

In this experiment, mechanical pressure is applied to the piezo crystals to produce voltage. The pressure level and pedestrian walking pace have an impact on the quantity of voltage generated. Using a statistical tool built into the SPSS software, sensitivity analysis is carried out between the voltage and the variables. The calculated P value must be less than 0.05 because the statistical calculations are done at a 95% significance level (SL). The statistical results for cases 1 and 2 are displayed in Table 10.4. In rubber strips with embedded piezos (case 2), both the pressure level and the walking speed show P values below the chosen SL (0.05).

It suggests that these elements significantly affect the creation of voltage. Only the pressure level in the piezo without rubber strips (case 1) displays a P value that is less than the chosen SL (0.05). It suggests that the pressure level has a substantial impact on voltage generation, although the influence of walking speed is negligible. Due to their non-resilient nature, piezo crystal surfaces can sustain unrecoverable deformations. With an increase in walking speed, these irreversible deformations provide less voltage generation.

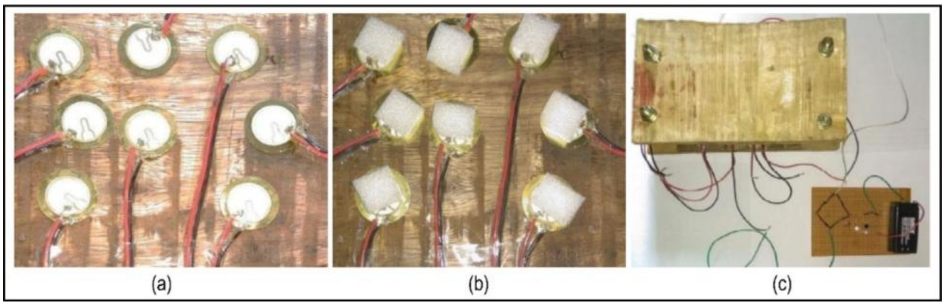


Figure 10.5 (a) Piezo crystals on wooden frame; (b) Crystals covered with sponge and (c) Overall setup.

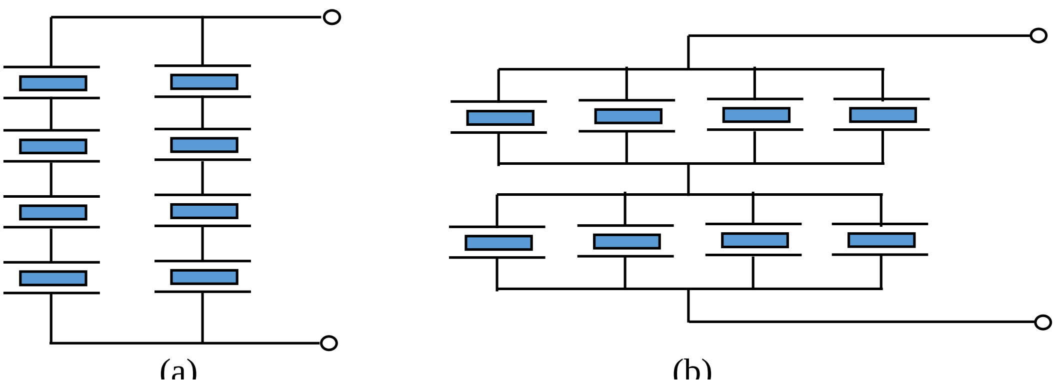


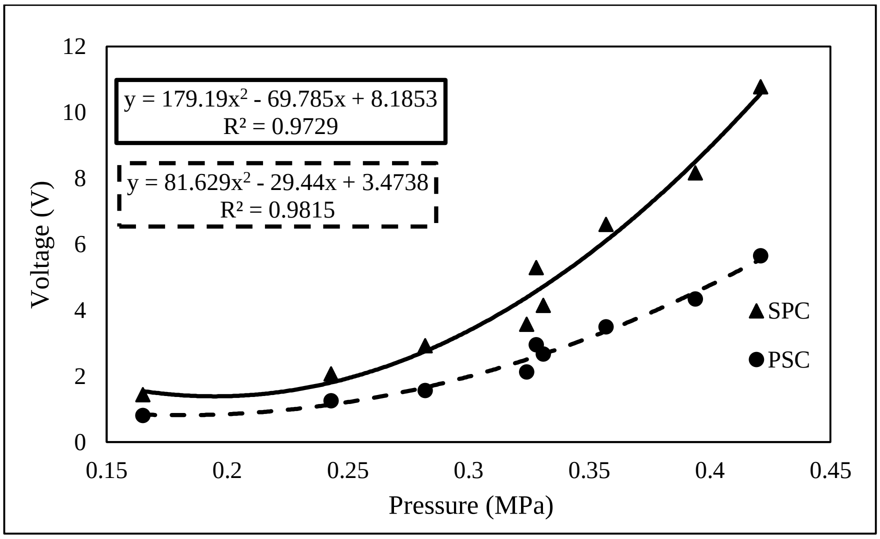
Figure 10.6 (a) Series-Parallel Combination (SPC) and (b) Parallel-Series Combination (PSC)

Table 10.4 Voltage Generation for Piezo without Rubber Strips

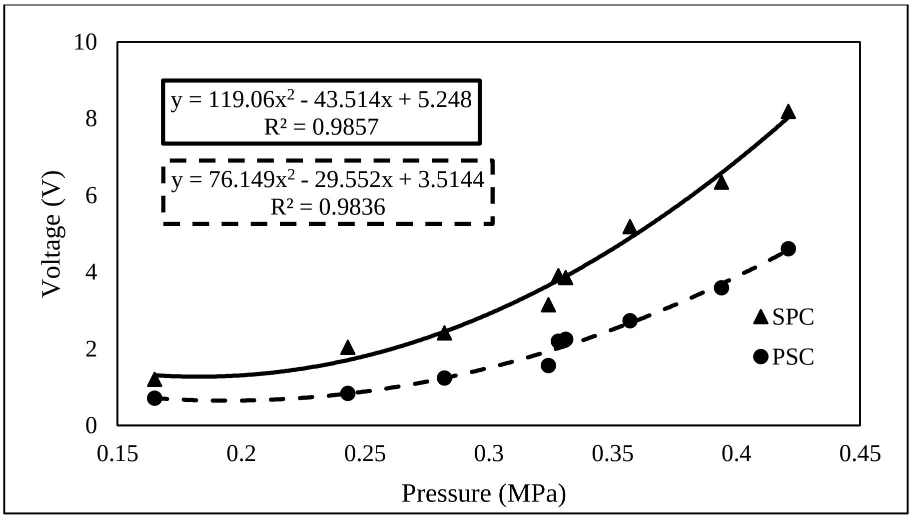
Person weight (kg)	Average shoe length (cm)	Pressure (kg/cm^2)	Voltage (volts)			
			Lower speed		Normal speed	
			SPC	PSC	SPC	PSC
15	15.1	0.165	1.2	0.71	1.44	0.81
25	15.7	0.243	2.04	0.84	2.07	1.26
35	18.4	0.282	2.41	1.24	2.92	1.57
45	19.9	0.324	3.15	1.56	3.57	2.13
55	22.0	0.331	3.86	2.25	4.15	2.67
65	25.3	0.328	3.91	2.2	5.29	2.95
75	27.3	0.357	5.18	2.73	6.6	3.5
85	27.9	0.394	6.34	3.59	8.16	4.34
95	29.1	0.421	8.19	4.61	10.77	5.65

Table 10.5 Voltage Generation for Piezo Embedded Rubber Strips

Person weight (kg)	Average shoe length (cm)	Pressure (kg/cm^2)	Voltage (volts)			
			Lower speed		Normal speed	
			SPC	PSC	SPC	PSC
15	15.1	0.165	1.78	0.75	1.96	0.92
25	15.7	0.243	2.71	1.08	3.42	1.56
35	18.4	0.282	3.46	1.62	4.26	1.98
45	19.9	0.324	4.42	2.57	5.81	3.12
55	22.0	0.331	5.05	3.12	6.41	3.72
65	25.3	0.328	4.7	2.65	6.45	3.38
75	27.3	0.357	6.54	3.21	8.19	4.65
85	27.9	0.394	8.17	4.56	10.15	5.91
95	29.1	0.421	10.31	5.98	13.32	7.12

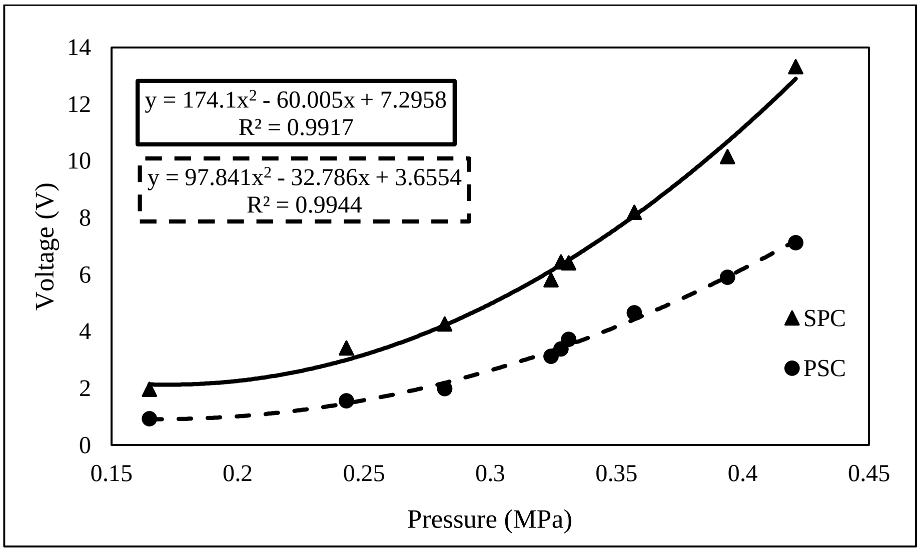


(a) Normal speed

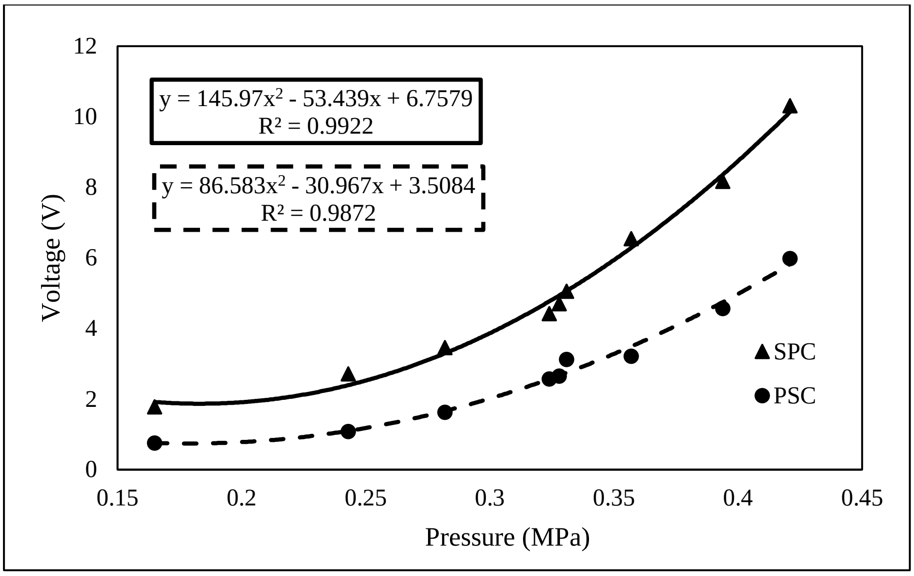


(b) Lower speed

Figure 10.7 Variation of Voltage with Pressure in case of Piezo without Rubber Strips



(a) Normal speed



(b) Lower speed

Figure 10.8 Variation of Voltage with Pressure in Piezo embedded Rubber Strips

Case 1: Pedestrians, moving at normal speed, produce possible output voltage for Location (L_1) which is obtained by multiplying the number of pedestrians with corresponding voltage

$$= \frac{1}{800}\begin{bmatrix}(108\times 1.44)+(193\times 2.07)+(324\times 2.92)+(620\times 3.57)+(837\times 4.15)+ \\ (1554\times 5.29)+(1356\times 6.6)+(521\times 8.16)+(312\times 10.77)\end{bmatrix} = 40Volts$$

Similarly, the possible output voltage is generated from different locations found as 37V, 35V, 29V, 25V, and 22V for L_2, L_3, L_4, L_5, and L_6. The number of super capacitors (charging voltage 2.5V) required at a particular location has been decided on the basis of electricity generated at different locations and is listed in Table 10.7.

For location L_1 (16 numbers capacitor bank):

The energy available to store the capacitor bank $= \frac{1}{2}cv^2$

Where, c= capacitance and v = charging voltage.

Energy = $0.5\times 16\times 10\times 2.5^2$ = 500J [considering c = 10 Farad; v = 2.5V and number of capacitor = 16]

500J energy will be produced with single footstep of crowd at L1 if total 16 capacitors (10F) are connected on series connection and charging voltage of each capacitor as 2.5V.

Similarly, the energy will be generated at other locations for case 1 and case 2 is shown in Figure 10.9 and Figure 10.10, respectively.

Table 10.6 Statistical Values for Voltage Generation

Piezo embedded rubber strips				
	Coefficients	Standard Error	t Stat	P- Value
Intercept	-8.60108	1.721091	-4.99746	.000
Applied pressure	37.21432	3.932403	9.463507	.000
Walking speed	0.691667	0.2887	2.395794	.030
Piezo without rubber strips				
	Coefficients	Standard Error	t Stat	P- Value
Intercept	-7.19262	1.657548	-4.33931	.000
Applied pressure	30.92394	3.787219	8.165342	.000
Walking speed	0.482778	0.278042	1.736351	.102

Table 10.7 Number of Capacitor Banks Required at Various Locations

Location	Case 1		Case 2	
	Normal speed	Lower speed	Normal speed	Lower speed
Post office ch. (L_1)	16	12	20	16
Math ch. (L_2)	14	12	19	15
Kaman ch. (L_3)	14	11	18	14
Motar stand ch. (L_4)	12	9	15	12
Paradise ch. (L_5)	10	8	12	10
RMS ch. (L_6)	9	7	11	8

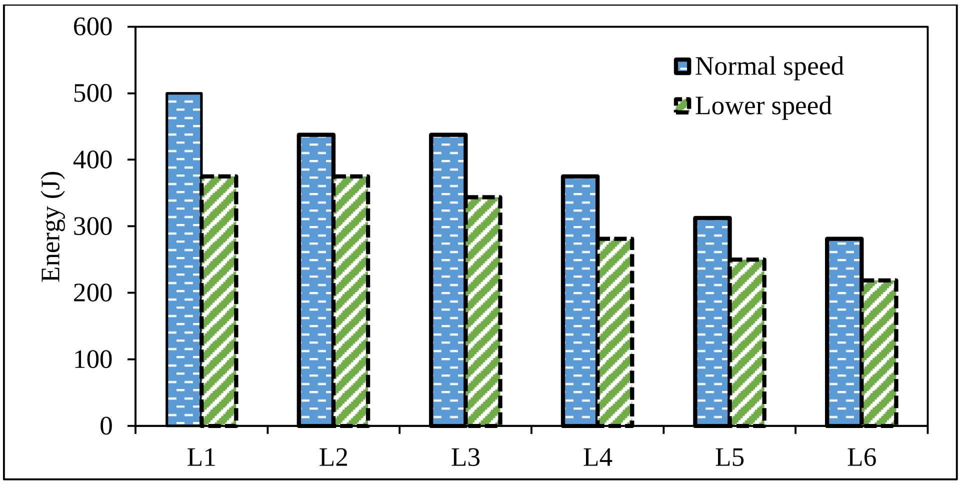


Figure 10.9 Energy Generated by Single Footstep in Piezo without Rubber Strips

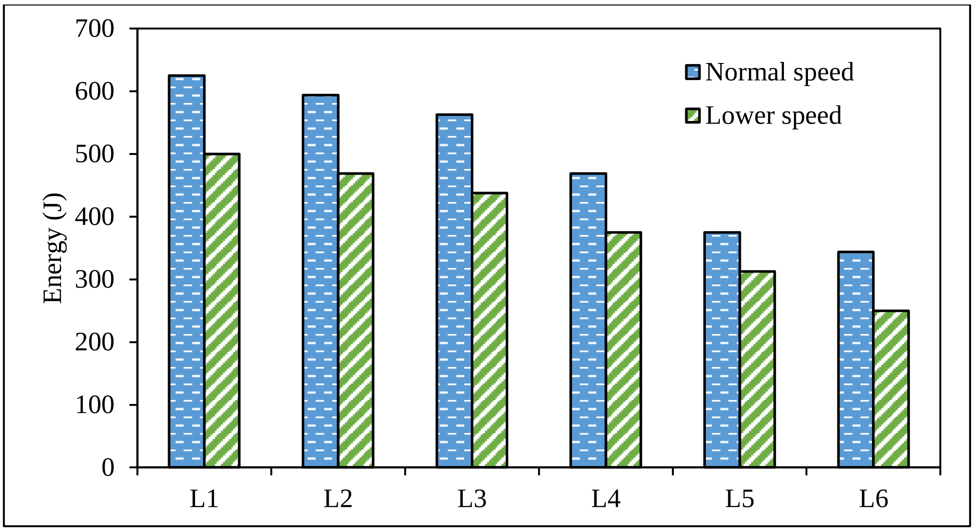


Figure 10.10. Energy Generated by Single Footstep in Piezo Embedded Rubber Strips

10.4 Findings of the study

Research is being done to identify novel alternative materials for efficiently generating power due to the dearth of non-renewable energy sources. Utilizing unconventional sources for energy harvesting has grown increasingly important in recent years. In this work, electricity is produced on footpaths using piezoelectric materials implanted with or without rubber strips. The subsequent inferences can be drawn from the test findings.

- It has been found that mechanical dampening has an inverse relationship with maximum output power. Rubber materials are utilized because of their low damping. In order to generate voltage, the piezoelectric materials with rubber strips incorporated function better than those without them.
- Piezoelectric materials combined in Series-Parallel combinations (SPC) generate voltage more effectively than those connected in Parallel-Series combinations (PSC).
- In all cases, the amount of voltage generation increases with the increase in pressure level and walking speed.
- Sensitivity research shows that for piezo materials embedded with rubber strips, both the pressure level and the walking speed have a substantial impact on voltage generation.
- In a congested area, a single tread on piezoelectric materials with and without rubber strips, respectively, can generate 625 J and 500 J of energy (L1). Therefore, compared to materials without rubber strips, piezoelectric materials with integrated rubber strips produce 25% more energy.

This technique of electricity generation can be utilized to efficiently meet the minor and daily energy needs for things like charging mobile devices and LED lighting. The general public, particularly pedestrians, may find this new option handy.

CHAPTER- 11
COST ANALYSIS

11.1 Cost Analysis of the work:

Any new technology is liable to be used based on its cost-effectiveness. In developing countries like India, the economy plays an important role in the growth of the country. Cost-effectiveness and environmentally sustainable materials are always preferable. The current research has been found to be environmentally sustainable. At the same time, the cost-effectiveness of its field application is also to be verified. Keeping this in view, the cost analysis of the present research work has been performed as per the Pradhan Mantri Gram Sadak Yojana (PMGSY) Tripura Schedule of Rates 2023 and is presented below.

Table 11.1 Cost Analysis of Conventional Asphalt Pavement

Layer detail	Length (m)	Width (m)	Thickness (m)	Unit	Total quanity	Rate (Rs)	Total (Rs)
Sub-Base Course (WBM-II)	1000	3.75	0.15	cum	562.50	7525.80	4233262.50
Base-Course (WMM)	1000	3.75	0.15	cum	562.50	6267.20	3525300.00
Prime Coat	1000	3.75	-	sqm	3750	45.60	171000.00
Tack Coat	1000	3.75	-	sqm	3750	15.40	57750.00
Pre-Mix Carpet (20 mm)	1000	3.75	-	sqm	3750	270.30	1013625.00
Seal Coat (6 mm)	1000	3.75	-	sqm	3750	51.60	193500.00
						Grand Total	**91,94,438.00**
Rupees Ninety One Lakh Ninety Four Thousand Four Hundred Thirty Eight							

Table 11.2 Cost Analysis of Porous Asphalt Pavement

Layer detail	Length (m)	Width (m)	Thickness (m)	Unit	Total quanity	Void %	Reduced Quantity	Rate (Rs)	Total (Rs)
Geotextile Sheet Layer (75 mm)	1000	3.75	-	sqm	3750	-	3750	1150	4312500.00
Reservoir Course	1000	3.75	0.2	cum	750	35	487.50	6267.20	3055260.00
Choking Course	1000	3.75	0.025	cum	93.75	30	65.625	5357	351553.00
Porous Asphalt Layer	1000	3.75	0.05	cum	187.50	18	153.75	12782	1965233.00
								Grand Total	**96,84,546.00**
Rupees Ninety Six Lakh Eighty Four Thousand Five Hundred Forty Six									

In the cost analysis, low volume road having width 3.75 m and length of 1 km is considered for both conventional and porous asphalt pavements. The layer detail of conventional asphalt pavement is considered as per the current PMGSY guideline, and the layer detail of porous asphalt pavement is considered as per US Transportation Research Board. In comparison to conventional asphalt pavement, porous asphalt pavement is layered with voids to allow percolation of water and reduction in noise level. From the cost analysis, it is observed that the total cost of conventional asphalt pavement is obtained Rs. 91, 94,438.00 (Rupees Ninety One Lakh Ninety Four Thousand Four Hundred Thirty Eight), and the total cost of porous asphalt pavement is obtained Rs. 96, 84,546.00 (Rupees Ninety Six Lakh Eighty four Thousand Five Hundred Forty Six). From this cost analysis, it is observed that as compared to the conventional asphalt pavement, porous asphalt pavement is found 5% more expensive. Although the porous asphalt pavement is found little expensive as compared to the conventional asphalt pavement, but considering the environmental sustainable benefits of porous pavement, it may be proposed to be used for pavement construction.

CHAPTER-12

CONCLUSION AND RECOMMENDATION

12.1 Summary:

This study investigated the performance of the pervious pavement prepared with alternative and waste materials like low-density polyethylene (LDPE), Crumb Rubber, Ground Granulated Blast Furnace Slag (GGBS), steel slag, etc. Due to its advantages in terms of hydrology and the environment, pervious concrete is a well-known and developing technology today. As a result of the widespread adoption of this technique, pervious concrete pavement is now considered essential, particularly in urban areas. The application of pervious concrete pavement, however, is not a well-known practice in India. In addition, waste materials are used in this study to create the porous mix. Various studies have been conducted related to the use of waste and alternative materials in flexible and rigid pavement, but the use of waste materials in pervious pavement is a new concept, and in this respect, the present has great importance. Various laboratory tests have been performed to characterize the properties and performance of previous mixes using waste materials. On the other hand, it is important to prioritize the use of renewable energy sources when producing electricity. However, the energy that pedestrian movement on the sidewalk or roads releases is not put to use. However, using fossil fuels to produce power pollutes the environment and gradually depletes these non-renewable resources. Furthermore, piezo crystals embedded in rubber have been examined as an energy harvesting solution for footpaths.

12.2 Conclusions:

Based on the current study, the following major conclusions are drawn.

- The first part of this research aims to increase the strength of porous mixes by controlling their permeability. Low-density polyethylene (LDPE) is a water-resisting material. From the current study, it is observed that an increase in plastic content enhances the moisture resistance and also decreases the permeability of the mix. According to trial results, the blend provides improved Marshall Stability and quotient values at 0.50% plastic content, which are satisfactory in nature and meet MORTH specifications. At this percentage of plastic content, the permeability value is also found to be better than other types of mixes, and the value also complies with the MORTH Specification.

- The addition of Crumb Rubber and nanosilica to the open-graded Friction Course has improved the quality of the mix while lowering the optimum bitumen content, which has decreased the use of bitumen. From the test results, it is observed that the stability of the RPA mixes is higher than that of the unmodified mix. But the addition of crumbs in higher percentages reduces the air voids in the mix. It is also observed from the experiments that at 1% crumbs of rubber along with 2% nanosilica, the RPA mix gives a better stability value with a satisfactory permeability value. Addition of nanosilica also enhances permeability while decreasing indirect tensile strength.
- When compared to coarse natural rock aggregates, coarse steel slag aggregates have better physical qualities. However, coarse steel slag aggregates outperform coarse natural rock aggregates in terms of water absorption. However, no aggregate absorbs water more than the maximum limit of 2%. The physical characteristics of SSA mainly meet the Marshall Specification for the Design of Porous Asphalt Concrete. For SA-NA20, SA-NA40, and SA-NA60 samples made with 5% bitumen content, different experiments have been performed, and it has been observed that the SA-NA40 mix gives better results in all respects as compared to other mixes. The findings of laboratory research suggest that SSA is especially helpful for use in India to lessen its reliance on natural stone aggregate.
- In this study, GGBS is added to the mix as a partial replacement for cement to check the viability of the material in terms of mechanical and hydrological parameters. Mixes have been prepared with a w/c ratio of 0.30 and 0.32. From the experimental results, it is found that when GGBS is included in the mixture, the strength in compression, split tensile strength, and flexural strength are all improved. While permeability and porosity are reduced, strength measures are improved by using fine aggregates with higher GGBS concentrations.
- High-occupancy vehicles (HOV), such as large and medium-sized buses and trucks, travel in fewer numbers in cities like Agartala, Tripura. Since HOVs are moving less in number, small vehicles are occupying more space in the total traffic count. As a result, noise pollution is increased, and the vehicle noise survey reveals that it exceeds the limiting range as per Indian Standards (In commercial areas, during the day and night, the noise level is 65 dB (A) and 55 dB (A), respectively). After conducting experimental work in the lab and observing traffic movement on the test track of porous pavement, it was observed that traffic noise has been reduced by 4-5% on the porous pavement as compared to conventional impervious pavement.
- Aggregate gradation is one of the important parameters in the design of porous mixes. Different shapes and sizes of coarse aggregates like flaky, angular, and irregular have been used in the preparation of samples in this study at two types of W/C ratios of 0.30 and 0.35. In the

experimental study, it was found that varying shapes and sizes of coarse aggregates influence the strength and hydrological properties of the mixes. Among all types of mixes, I-20, i.e., the irregular shape of aggregate, gives better results at both water-cement ratios of 0.30 and 0.35.

- Rubber strips incorporated into piezo produce better outcomes than piezo without rubber strips at capturing energy from pedestrian movement. Series-Parallel Combination (SPC)-connected piezo crystals exhibit superior performance to Parallel-Series Combination (PSC)-connected piezo crystals. Piezo crystals with rubber strips provide 25% more energy than piezo crystals without rubber strips in SPC. This process's power output can cover a few small energy needs. This new option could be very beneficial for the expansion of road infrastructure if properly implemented.
- From the cost analysis, it is observed that porous asphalt pavement is 5% more expensive as compared to the conventional asphalt pavement. But considering environmental sustainability aspects, porous asphalt pavement is viable and may be considered for the construction of pavement.

These findings emphasize the efficacy of various changes and materials in enhancing the strength, permeability, and energy efficiency of various construction and power generation applications.

12.3 Uniqueness and Field Application of the work:

Porous Pavement is a pavement system which has the capacity to control rainwater. By decreasing the surface runoff, it can ensure the percolation of rain water through soil beneath. Moreover, it reduces the load on rainwater drainage systems, and danger of erosion & flooding. As rainfall runs over porous pavement, it filters naturally, removing pollutants and toxins. In current research also, similar property has been found through laboratory experiments. Urban noise level was measured in the research and it was found that conventional pavement is unable to reduce the noise level. In the contrast, porous pavement was found a good absorber of noise from the experiments and field observation performed in the present research. Due to these unique properties, porous pavement is becoming popular globally day by day.

12.4 Recommendations from this study:

After extensive experimental work and analyses, this study recommends the use of waste materials in the pervious pavements in urban areas for controlling storm water. The study also aims to harvest energy produced during the movement of pedestrians on the footpaths of the roads. Based on the study, the following recommendations can be made:

- Low-density polyethylene (LDPE) may be used at 0.50% by mass of the mix for the preparation of Porous Asphalt mix.
- Another waste material, Crumb rubber, may also be added at 1% along with 2% nano-silica for the preparation of Porous Asphalt mix for better results.
- CSSA may be used in permeable asphalt pavements to improve stability, strength, and permeability, making it an acceptable replacement for natural aggregates.
- GGBS may be used as an alternative material for the partial replacement of cement. While deciding the content of GGBS, the trade-off between increased strength and decreased permeability and porosity may be considered.
- The use of LDPE at 0.5% in the porous asphalt mix reduces the noise pollution on porous pavement surfaces by 4-5% as compared to conventional impervious pavement.
- Irregular-shaped coarse aggregates of the 20 mm size range possess lower porosity and permeability but higher strength characteristics. So this shape of coarse aggregates may be used in the preparation of porous concrete mixes.
- Because of their greater power and voltage generation capabilities, piezoelectric materials containing rubber strips should be used for energy generation on walkways and footpaths.

CHAPTER- 13

FUTURE SCOPE OF THE WORK

13.1 Future scope:

Based on the findings of the numerous studies, the suggestions that follow for further study and development in relevant disciplines might be made:

- Research may be carried out on the long-term effectiveness and reliability of permeable bituminous pavements with varied plastic content under various traffic and environmental circumstances.
- A life-cycle cost analysis may be performed to determine the economic feasibility of employing plastic-modified permeable bituminous pavements over traditional pavements.
- Research may be conducted on the long-term aging effects on the characteristics of crumb rubber-modified bituminous concrete to assure its long-term viability.
- A study may be carried out on field testing and ongoing monitoring of CSSA-based permeable asphalt pavements to evaluate their performance and long-term viability in real-world settings.
- An investigation may be done on the use of GGBS in conjunction with various supplemental cementitious materials to increase pervious concrete strength and permeability.
- Research may be conducted thoroughly on noise pollution in various metropolitan locations to analyze the efficiency of porous asphalt with varied plastic contents in decreasing noise levels and the need for maintenance of porous asphalt surfaces for noise pollution management.
- An investigation may be done on the use of novel aggregate forms and materials to improve concrete performance as well as sustainability.
- Durability aspect is essential for any type of work. This type of porous pavement is durable as per the research done by U.S. Department of Transportation. However, detail study on durability may be done in future.
- A study may be conducted on more efficient and durable piezoelectric materials embedded on the road surface.
- Investigation may be performed on the combination of piezoelectric power production devices with energy storage as well as grid infrastructure for optimal electricity consumption.

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- IS: 2386 (Part-4)-1963, Methods of test for aggregates for concrete, Mechanical Properties.

ANNEXURE

Intellectual Property Office

Certificate of Registration for a UK Design

Design number: 6284505

Grant date: 07 June 2023

Registration date: 20 May 2023

This is to certify that,

in pursuance of and subject to the provision of Registered Designs Act 1949, the design of which a representation or specimen is attached, had been registered as of the date of registration shown above in the name of

Dr. Manish Pal, Dr. Kaberi Majumdar, Mr. Debashish Karmakar, Dr. Dipankar

Sarkar, Dr. Joyanta Pal, Dr. Pankaj Kumar Roy

in respect of the application of such design to:

Intelligent road mock-up

International Design Classification:
Version: 14-2023
Class: 25 BUILDING UNITS AND CONSTRUCTION ELEMENTS
Subclass: 02 PREFABRICATED OR PRE-ASSEMBLED BUILDING PARTS

Version: 14-2023
Class: 20 SALES AND ADVERTISING EQUIPMENT, SIGNS
Subclass: 02 DISPLAY AND SALES EQUIPMENT

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An Experimental Study on Porous Asphalt Pavement for the Improvement of Strength under Medium Traffic Condition Maintaining Permeability

Debashish Karmakar[a], Dwipjoy Debnath[b], Manish Pal[c], Pankaj Kumar Roy[d] and Kaberi Majumdar[e]

a.Assistant Professor, Dept of Civil Engg, NIT Agartala, India, debashishkarmakar05@gmail.com
b.M.Tech Scholar, Dept of Civil Engg, NIT Agartala, India, dwipjoydebnath95@gmail.com
c.Professor, Dept of Civil Engg, NIT Agartala, India, mani_nita@yahoo.co.in
d.Professor, School of Water Resources Engg, Jadavpur University, India, pk1roy2014@gmail.com
e.Assistant Professor, Dept of Electrical Engg, TIT Agartala, India, majumdark590@gmail.com

ABSTRACT

Porous Pavement is used for its benefits in the reduction of water runoff, improvement of water quality, developing skid resistance of the pavement surface during heavy rainfall. The aim of present study is to improve the strength characteristics of Porous Asphalt Pavement. But it can be noted that with increase in strength, the permeability of porous pavement will be reduced. Hence, the improvement of strength should not affect the permeability property. An Open-Graded Friction Course (OGFC) bituminous mix, which is widely known as Porous Asphalt (PA) is a mixture having gap graded aggregate. It is generally used as a surface course in pavement. This study focuses on crumb rubber modified bituminous mix for Porous Asphalt layer under medium traffic load. A porous asphalt pavement is normally used to infiltrate rainwater through pavement into the natural ground surface that helps to recharge the ground water layer. In this research, the effectiveness of using crumb rubber (CR of 0.5%, 1%, and 1.5% by weight of aggregate) in dry process with PA mix is evaluated. This study abbreviates the result of experimental work done in laboratory to investigate the properties of RPA mix and compared it with conventional OGFC bituminous mix as per ASTM D7064/D7064M. Marshall Mix design is performed for determining the Optimum Bitumen Content (OBC), Marshall Stability, flow, Marshall Quotient. The result shows that the RPA gives desired stability value at 1% crumb rubber content with 5% OBC, which is considerably higher as compared to conventional PA mix.

Keywords: Open-Graded Friction Course (OGFC) bitumen mix, Porous Asphalt (PA), Rubberized Porous Asphalt (RPA), Optimum Bitumen Content (OBC), Marshall Mix design.

1.0 Introduction

Urbanization and industrialization have been accelerating rapidly due to the overall growth of the civilization and the increment of the population throughout the world. Continuous deforestation and encroachment on forested land and rural areas for the sake of urbanization and industrialization are in rise. As a result, the process of urbanization has doleful effect on the environment and leads to the rise of deforestation. For instance, the construction of roadways, railways, airports, commercial buildings etc. are covering a considerable track of open land with non-porous concrete construction disrupting the free flow of surface water to reach the underground water table. As a result, the huge quantity of rainwater cannot percolate through the non-porous surface that leads to

Chapter 6
A Study on Porous Bituminous Pavement as an Alternative Method for Ground Water Management

Debashish Karmakar, Bappi Das, and Manish Pal

Introduction

Porous bituminous pavement is typically referred to as Open Graded Asphalt Concrete (OGAC). This pavement technology is also known as Open Graded Friction Course (OGFC) [5]. This technology allows rainwater to percolate through the pavement structure. There are mainly two types of road constructions in India i.e. flexible pavement and rigid pavement. Flexible pavements are bitumen roads whereas rigid pavements are concrete roads. Because of cost constraints, network of bitumen roads is more in India. But the problem faced by bitumen roads is that these roads require regular maintenance. In most parts of India disintegration of pavement surface due to rainwater accumulation is a major issue. As a result of disintegration of pavement many potholes are created. One of the main reasons why the idea of porous bituminous pavement is mainly brought up in road construction is to find a solution to this growing problem of potholes and pavement disintegration due to rainwater. As this pavement technology does not allow rainwater to accumulate on road surface, it ensures less chance of pavement deterioration and potholes.

Moreover, many Indian cities are facing an acute crisis of water table depletion. According to National Institution for Transforming India (NITI) Aayog's report, 21 cities in India including New Delhi, Bangalore, Chennai and Hyderabad will run out of ground water by 2020 [1]. This will affect over 100 million people. Porous bituminous pavement can be thought of as one of the solutions to this severe

D. Karmakar (✉) · B. Das · M. Pal
National Institute of Technology Agartala, Barjala, Jirania, Tripura, India
e-mail: debashishkarmakar05@gmail.com

B. Das
e-mail: dasbappi273@gmail.com

M. Pal
e-mail: mani_nita@yahoo.co.in

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Experimental Analysis on Engineering Properties of Pervious Concrete with GGBS as a Partial Replacement for Cement

Debashish Karmakar[1*], Kaberi Majumdar[2], Manish Pal[3] and Pankaj Kumar Roy[3]
[1]Assistant Professor, Department of Civil Engineering, NIT Agartala, India.
[2]Associate Professor, Department of Electrical Engineering, Tripura Institute of Technology, Tripura, India.
[3]Professor, Department of Civil Engineering, NIT Agartala, Tripura, India.
[3]Professor, School of Water Resources Engineering, Jadavpur University, West Bengal, India.

(Corresponding author: Debashish Karmakar)*
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ABSTRACT: Porous Concrete has been developed as an emerging technology, since this is environmentally and hydrologically sustainable. The use of porous concrete is limited to parking lots, walkways, footpaths etc. But to use porous concrete on the road for vehicular movement is a challenge for any researcher. The current approach is to use porous concrete on the low volume road by improving the engineering properties. Using a variety of design criteria, this study prepares a number of test samples before examining the characteristics like strength and permeability of porous concrete mixes. Regarding characteristics such as flexural strength, permeability, compressive strength, tensile strength, and porosity the effects of cement-water ratio, aggregate gradation, and fine aggregate's percentage are estimated. Different samples of pervious concrete mixtures have been produced and experimentally tested employing aggregate sizes 20-16 mm, 16-12.5 mm, and 12.5-4.75 mm. In the study water-cement ratio is considered as 0.30 and 0.32. The presence of GGBS in the permeable concrete was evaluated using a systematic investigation through the compressive strength and permeability property. In this experimental initiative, it is suggested that GGBS may be utilized to partially replace cement. The percentages of replacement were considered as 25 percent, 30 percent, 35 percent and 40 percent. The combination started to lose its stability once we reached the maximum level of 40%. The split tensile strength, flexural strengths and, compressive strength were all improved with a 40% substitution. The GGBS has been raised, yet it has decreased permeability. The current study has improved the structural and hydrological properties of porous concrete by adding GGBS at some selected percentage, and this improved mix may be used for the preparation of porous concrete layer for low-volume roads construction.

Keywords: GGBS, Water cement ratio, Aggregate binder ratio, Strength, Permeability.
Abbreviations: GGBS, Ground Granulated Blast-furnace Slag; M, Mix; MPa, Mega Pascal; CC, Cement Concrete.

I. INTRODUCTION

Water, port land cement, and coarse aggregate are the components of permeable concrete. The pervious concrete is considered as a pavement because of having environmental friendly aspects like hydrological and mechanical properties [4, 10, 14]. The use of pervious concrete had been restricted to the construction of footpaths, walkways, parking lots etc. But gradually this concept has been implemented in the carriageway construction. The challenge faced in this concept is to sustain against the moving traffic load. Since pervious concrete is an open-graded pavement, it can allow water to percolate through it easily, but it must desperately withstand the traffic load. The lack of fine particles in the mix sets it apart from regular concrete. The aggregate is typically one size, and the point of contact is where a cement and water paste is used to bind the material together [8]. To make a paste, a specific amount of water and cementitious materials are combined. When mixed and applied, the paste creates a thick layer over the aggregate particles to prevent it from leaking off. Pervious concrete creates a harsh mix that is challenging to mix and put because it lacks fine aggregate [7]. As a result, the concrete has a significant number of interconnecting voids. Water may swiftly percolate through concrete when it is appropriately constructed [13, 15, 23]. Contrary to pervious concrete, which has a void ratio that can range from 15 to 40 percent, ordinary concrete has a void ratio of between 3 and 5 percent. Pervious concrete has a low weight (between 1600 and 2000 kg/m^3) because to its large void content [2-3]. Depending on the use, the void ratio of pervious concrete varies. A large degree of surface ravelling and honeycombing may be seen on the pervious concrete's surface. Many researches have been performed to improve the strength of pervious concrete layer. Aggregate having different size and shape have been used to improve the strength parameters of pervious concrete [6, 18]. To improve the strength and durability properties of pervious concrete different types of additives like polypropylene fibre, polyethylene fibres, fly ash have been used [19]. Over burnt brick aggregate also has been used as coarse aggregate to check the behaviour of pervious concrete [22]. Different mix designs have been done to check and compare the performance of pervious concrete in terms of hydrological and strength properties [16, 17, 21].

In earlier researches, it is observed that although pervious concrete is an open-graded pavement, if it has satisfactory bonding with the aggregates then it can resist traffic load as well as allow percolation of water. GGBS is a material which is having cementitious property to have good bonding in the mix [1]. In order to produce ground-granulated blast furnace slag, iron slag is quenched from the source of blast furnace molten in aqueous media to

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Utilization of porous asphalt material in road construction for reducing the vehicular noise

Debashish Karmakar [a,*], Manish Pal [b], Kaberi Majumdar [c], Machavarapu Suresh [d], Pankaj Kumar Roy [e]

[a] School of Water Resources Engineering, Jadavpur University, West Bengal 700032, India
[b] Department of Civil Engineering, NIT Agartala, Tripura 799046, India
[c] Department of Electrical Engineering, TIT, Tripura 799009, India
[d] Department of Civil Engineering, Vignan's IIT, Visakhapatnam 530046, India
[e] School of Water Resources Engineering, Jadavpur University, West Bengal 700032, India

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ABSTRACT

All over the world the growth in traffic volume particularly in urban area has become serious concern. As a result, the traffic congestion is increasing and subsequently noise pollution is also increasing. It has been observed that major part of urban roads are constructed with asphalt pavement and the surface of this type of pavement is impervious in nature. Sound produced from traffic cannot be absorbed by the conventional impervious surface. The present study focuses on such solution so that the noise pollution produced by traffic can be reduced. Pavement made by porous asphalt material is a type of pavement which possesses permeable surface. Various roads of Agartala city of Tripura have been selected for conducting study on noise pollution produced by traffic and it is observed that in Old Motor Stand road, value of noise on conventional asphalt pavement (CAP) is 101.05 dB(A) and 92.10 dB(A) in day and night time respectively. The level of noise in other roads is also considerably higher than the standard limit. In this study, stone aggregates have been coated with plastic material (LDPE) at different percentages of 0.25%, 0.5%, 0.75% and 1% for the preparation of porous asphalt samples. After conducting Marshall Stability test, it is found that at 0.5% plastic content, porous asphalt mix gives higher stability, which satisfies the MoRTH guideline. Simultaneously it is also observed that the value of noise level is reduced by 4–5% after using Porous Asphalt Material (PAM) at 0.5% plastic content in the stone aggregate. So Porous Asphalt Pavement (PAP) may reduce the noise level and it may be considered as the alternative solution to reduce the noise pollution in urban area.

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1. Introduction

Porous Asphalt (PA) material may be used as a wearing surface in road construction. The porous surface should be highly permeable and free from clogging so that the rain water can drain off into the porous asphalt layer and followed by the stone bed, and then penetrates into the soil easily. The bottom layers must have adequate capacity to accommodate the water volume and it should not disturb the underground water layer [1–5]. The rain water passes into the porous asphalt layer and as a result many contaminants can be removed. The contaminants can be also removed by stone bed, and soils through filtration process [6]. In urban areas noise is one of the sources of pollution which can affect the human health. According to the World Health Organization (WHO), noise levels more than 70 dB (A) can impair the hearing ability. It also leads to anxiety and hypertension [7]. Roughness of the pavements is one of the major reasons for noise pollution produced by vehicles. Earlier studies focused on the influence of different types of pavements on the nearby acoustic atmosphere of roads, and gave a little attention to the noise levels produced by vehicles. In paved roads due to the movement of traffic there is friction between the tyres and pavement surface and it results in noise pollution. So the noise reducing surface technique may be a solution to mitigate the problem [8–10].

Porous Asphalt is an inventive road construction technology. It allows water to penetrate through the asphalt layer in the presence of air voids. This type of pavement can decrease the traffic noise

* Corresponding author.
E-mail address: debashishkarmakar05@gmail.com (D. Karmakar).

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Energy harvesting from pedestrian movement using piezoelectric material

Debashish Karmakar [a], Kaberi Majumdar [b], Manish Pal [a], Pankaj K. Roy [c], Suresh Machavarapu [a,*]

[a] Department of Civil Engineering, NIT, Agartala, Tripura 799046, India
[b] Department of Electrical Engineering, TIT, Narsingarh, Agartala, Tripura 799015, India
[c] School of Water Resources Engineering, Jadavpur University, West Bengal 700032, India

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ABSTRACT

With the lapse of time, attempts are being made to find out alternative materials as sources of energy to meet the increasing energy demand. Present work aims at energy harvesting from pedestrian movement over piezoelectric material with or without rubber strips. Pedestrian data have been collected from six locations of Agartala city, India. To get more power, mechanical damping is kept low using piezo embedded rubber strips. Piezoelectric materials embedded with rubber strips yield better results than that without rubber strips. Piezoelectric materials connected in Series Parallel Combination (SPC) give better results compared to Parallel Series Combination (PSC). Sensitivity analysis shows that pressure level and walking speed significantly affect the voltage generation. The energy generated by this process can be stored up in super capacitors that meet minor energy requirements such as lighting a small powered LED light on the roadside, charging mobile phones etc.

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1. Introduction

Energy is the quantitative property to perform different physical, mechanical and other activities. The most important energy is the electrical energy which is generally obtained by using natural resources. Huge power plants are set up at a heavy cost for the generation of electricity. The use of fossil fuels like natural gas, oil, coal etc. for the generation of electricity leads to shortage of the natural deposits of raw materials. On the other hand, it releases pollutants into the environment. To solve the crisis of electricity researchers are out to find new methods for obtaining more electricity from other alternative materials without causing any harm to the balance of nature. Several researchers have proved that the hydraulic, solar and wind energies are to be substitutive for fossil fuels in electricity generation [1–3]. Piezoelectric energy harvesting technique has its advantages [4,5]. This power generation technology is easy to install and not hazardous and has gained substantial attention since the last decade [6]. Amount of energy collected from piezoelectric crystal materials depends on the extent of deformation of the used crystals. The stored energy can cause improvement in the efficiency of the system. Energy harvesting or energy storing technique is a procedure which includes gathering, accumulating, and distributing unused energy for human activities [7]. In recent years, energy harvesting technology through transduction has played an important role in solving the ever-increasing energy requirement [8].

Three types of approaches are implemented for energy harvesting e.g. electrostatic, electromagnetic, and piezoelectric. Energy harvesting through piezoelectric transduction proves to be the most promising one [9–11]. No byproducts are produced during the process and act as environment-friendly. The amount of power generation through piezo crystal is inversely proportional to the mechanical damping. In this study, piezo crystals are sandwiched between two rubber strips because of its low damping. This work focuses on energy harvesting from the movement of pedestrians through piezo embedded footpath with/without rubber strips.

2. Literature review

Pavement structure is constructed with carriageway and footpath, which continuously carry vehicular loadings and pedestrians. The energy released during the vehicular and pedestrian move-

* Corresponding author.
E-mail address: machsuresh@gmail.com (S. Machavarapu).

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