DEVELOPMENT OF GEOPOLYMER BASED POROUS CONCRETE

A thesis submitted to fulfillment of the requirements for the degree of

Master in Civil Engineering

Submitted By

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UNDER THE GUIDANCE OF

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CERTIFICATE OF RECOMMENDATION

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CERTIFICATE OF APPROVAL

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<u>DECLARATION</u>

*I, Jayanta Halder, a student of Master of Engineering in Civil Engineering (Structural Engineering), Jadavpur University, Faculty of Engineering & Technology, hereby declare that the work being presented in the thesis work entitled, "***Development of Geopolymer Based Porous Concrete***", is authentic record of work that has been carried out at the Department of Civil Engineering, Jadavpur University, under the guidance of Prof. (Dr.) Saroj Mandal, Department of Civil Engineering, Jadavpur University.*

The work contained in the thesis has not yet been submitted in part or full to any other University or institution or professional body for award of any degree or diploma or any fellowship.

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Abstract

All the commercial road pavements are impervious in nature. It creates some major problems for the environment as well as road users for example, heat island and extra storm water on road surface. Researchers have already studied cement based no fines concrete termed as porous concrete and examined its performance in various laboratory and field condition. It confirms a functional porous concrete mixture (cement based) as a sustainable pavement material in low traffic or loading areas. This highly porous material is found beneficial for both the environment and human beings on the earth surface because it has the great ability to mitigate the heat islands and storm-water run-off. It also helps filtering run-off water, minimizing acoustic noise pollution and recharging groundwater storage. Even it is getting practiced in United State, Japan, England and Australia from last few years because of such properties. However, its application is very limited to permanent construction because of low strength and high voids content. Thus, the porous concrete material needs improvement particularly the strength property without compromising its porosity and low cost.

On the other hand, geopolymer, invented by J. Davidovit, may be used for various engineering purposes due to its excellent performance under compression, good acid resistance, low creep and drying shrinkage and long-term durability. Presently, it has been established as an alternative binding material of cement as a construction material for the various environmental benefits mainly reducing Carbone dioxide (CO_2) emission to the atmosphere. So, the use of geopolymer would be greener if the cement is wholly replaced by the geopolymer binder.

However, the main objective was to improve the strength property and to find an optimum mixture proportioning of geopolymer based porous concrete having porosity in the range of 15% to 25%. Particularly to enhance its strength property, the effect of addition of small amounts of sand along with a combination of two different single sized coarse aggregates into the geopolymer based porous concrete has been proposed. Whereas the main purpose of this study is to investigate the performance of different mixes in term of strength and water permeability coefficient.

In this present laboratory investigation, low Calcium fly ash (class F) collected from the coal thermal power plant and locally available Sodium based alkaline activator was the main binding materials in the preparation of geopolymer binder. A blend of two typical single sized coarse aggregate type I (pass through 12.5 mm and retain on 10 mm sieve) and coarse aggregate type II (pass through 10 mm and retain on 4.75 mm sieve) has been used as an inert material into the geopolymer based porous concrete. A modified method for the activation of geopolymer paste has been adopted where the mixture of fly

ash and Sodium based alkaline activator are heated at 60˚C for 2 hours to accelerate the polymerization process. Little amount of sand (7% by mass of total coarse aggregates) was also mixed with the geopolymer paste for 1-2 minutes prior to complete geo-polymerization and then immediately mixed with coarse aggregates. Curing of the entire specimen was done at ambient temperature (27 ± 2ºC, RH 65%) condition. This mixing process makes the geopolymer porous concrete easy to use in field construction. Three different fly ash to coarse aggregate ratios (by weight) of 1:4, 1:4.5 and 1:5 have been maintained for each of the three alkaline activators to fly ash ratios of 0.40, 0.39 and 0.38. In this report, the effects of influential parameters such as alkali activator to binder ratio, fly ash to aggregates ratio, water to solid ratio on the strength, water permeability and porosity has been discussed in detail.

Based on the present experimental study and test results, it is concluded that the low calcium fly ash could be used as source material in geopolymer binder for the preparation of porous concrete. In India, proper mix designing and testing procedure have not yet been developed for geopolymer based porous concrete. However, more experimental data is required on various engineering and mechanical performance of geopolymer based porous concrete before use in practical application as paving material.

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Chapter 1

1.1 Introduction

Porous concrete is a special type of concrete material having an appropriate strength ranging from 4 to 31 MPa **[1, 2]**. It also has about 15% to 36% voids to pass the water fully through of concrete media **[2, 3]** to fulfill the minimum requirement of water permeability coefficient of 1 mm/sec**.** Its characteristics pore-size ranges from 2 mm to 4 mm **[4].** The porous concrete mixtures are normally made of binder materials such as cement, fly ash, GGBS etc., coarse aggregate, water and some admixture if needed.

The use of such porous concrete is generally limited to permanent construction and relatively recent, but it is being used as a building material in Europe, Australia, and the Middle East for over a long period. The earliest application of no-fines concrete was in the construction of two houses and a sea groyne of 61 m long and 2.15 m high in the United Kingdom in the year 1852. The porous concrete has also been used in Europe for parking areas, roof pavements, and in some minor roads application in Switzerland and England. The experience with porous concrete in the United States, New Mexico, and Utah was primarily in pavement applications. As a Portland Cement Concrete (PCC) permeable base course, it has been used in states such as California, Illinois, Oklahoma, and Wisconsin. Some other applications of porous concrete were as slab for tennis courts in France and greenhouse floors in the United States. But in India, the application of porous concrete is almost nil in practical fields.

The road pavements (both the flexible and rigid) are generally functioned as an impervious medium on the earth surface which creates two major problems (**a)** Change in hydrological aspects **(b)** Variation of surrounding thermal ambiance. In fact, it is responsible for the storage of water on road surfaces, which is increasing surface run-off and creating a hazard in traffic operation. Therefore, it requires extra storm water management scheme in heavy rainfall areas. In other ways, during summer or in daylight, the temperature of the pavement surface, as well as its surrounding areas is increased and released heat to the atmosphere at night, it causes thermal discomfort to the road users. This relatively hot region is termed as 'Heat Island' and this phenomenon is leading to the consumption of electricity for cooling purpose and increasing CO_2 production indirectly. However, porous concrete has been found to be one of the best storm water management schemes as material.

The porous concrete has great ability to pass the water through its pores. So, the stored storm water on pavements surface can easily penetrate into the soil strata below the porous concrete bed. It may help recharging groundwater storage, making the groundwater level up and reducing surface run-off water. It easily removes relatively large wastages present in the storm water by their small size pores (2 mm –

4 mm), which improves the quality of groundwater. In recent, a crisis of water due to the lowering of groundwater level mainly in India is the matter of concern, and forever implementation of porous concrete may be the best solution to this problem.

A lot of research papers have been published on cement based porous concrete and its uses. Marolf studied the effect of aggregate gradation to diminish noise pollution forms due to frictional interaction between tire and pavement surfaces **[5**]. They suggest single size coarse aggregates into the porous concrete mixture to minimize acoustic noise pollution in road traffic operation. Porous concrete is also good in heat absorption that can eliminate urban heat island effect. Even low strength porous concrete has been used as sidewalks, parking lots, recreation squares and sub-bases for conventional pavement **[1, 3].** Researchers have found porous concrete as sustainable pavement materials because of its high porosity and various environmental benefits such as controlling storm water runoff, recharging groundwater and removing water pollutants **[1].** But there have some disadvantages of porous concrete such as low strength due to high porosity and high maintenance requirement for clogging effect, which limits the use of porous concrete in broad applications. So, it will be more effective if we can enhance its strength property.

Another problem is that the temperature on the earth surface is increasing day by day i.e. Global warming. Greenhouse gases mainly CO_2, CO, SO_2, CFC, O_3 etc. are responsible for the Global warming effect. Today, the effect of construction material mainly cement has been found one of the main reasons for global warming due to CO_2 emission. Collections of data show that 1 ton of cement is responsible for the production of about 1 ton of CO_2 gas to the atmosphere **[6].** Among the greenhouse gases, CO_2 gas contributes about 65% of the total global warming. But cement industries contribute about 7% of the total global Carbon dioxide emission annually **[7, 8]**. As we know, the demand for cement concrete is second only after water and also increasing day by day. Thus, it may have suggested to avoid cement for construction purposes for the minimization of global warming. In 1978, J. Davidovits **[9**] discovered Geopolymer materials and noted that CO_2 gas emits from the production of the geopolymers is nearly 80% less than that of traditional Portland cement**.** So, it has been chosen as an alternative to cement binders. The theoretical basis of geo-polymerization as a major reaction mechanism of cementless concrete was established using Kaolinite [$Al_2Si_2O_5$ (OH)] and Potassium based alkaline activators. There are two main ingredients of geopolymer such as source material and alkaline activator. But the source materials should be rich in Silicon (Si) and Aluminum (Al). These could be from a geological origin or by-product materials such as Metakaolin, blast furnace slag, fly ash, bottom ash, silica fume, rice husk etc. Alkali activator is normally composed of alkali metal hydroxide and silicate solution. Mainly Silicon (Si) and Aluminum (Al) atoms are responsible for the geo- polymerization reaction. When alkali activator is mixed with the source material and heated at elevated temperature, the chemical reaction is accelerated and formed a three-dimensional poly-sialate structure through Si-O-Si, Si-O-Al, and Al-O-Al bonding. The chemical reaction is known as geo-polymerization reaction, and the crystal material formed by this process of the polymerization reaction is known as geopolymer binder. However, Geopolymer binder has gotten goodwill as a supplementary material of cement binder in construction areas for most eco- friendly, economical and excellent cementations property **[9]**. It may be mentioned here, that heat curing for a particular period of time just after casting geopolymer binder is needed to obtain appropriate strength. Previous research work on properties of geopolymer binder shows excellent strength property, good acid resistance, low creep and drying shrinkage value. Even no alkali-aggregate reaction can take place in geopolymer conventional concrete **[19-21**]. Thus, its use in porous concrete makes it more environments friendly, economical and durable. However, there is still a scope of study of geopolymer binding materials in porous concrete.

Based on this collective information, a laboratory experimental study has been conducted to examine strength and pore properties of geopolymer based porous concrete. Our main objective is to enhance strength substantially along with finding an optimum mixture proportion for geopolymer based porous concrete such that it will perform satisfactorily in low as well as in high traffic areas as a surface and base course paving materials by investigating compressive strength, tensile strength, porosity, and permeability. The study has been made to enhance the strength property using coarse aggregate type **I** (pass through 12.5 mm and retain on 10 mm sieve) and coarse aggregate type **II (**pass through 10 mm and retain on 4.75 mm sieve**)** in equal proportion. In our laboratory, a mixture of fly ash and alkaline activator is heated at 60ºC in a heat-controlled oven for 2 hours before mixing with coarse aggregate to develop early strength through the polymerization reaction. After casting, entire specimens have been cured under ambient temperature condition (27ºC ± 2ºC; RH 65%) till testing. This method of preparing geopolymer based concrete is not the same as followed by others. It makes easy to use geopolymer in the field. Also, it is a low heat treatment process that minimizes the energy consumption.

1.2 Objective

Use of conventional pavement materials makes the earth surface impervious which is mainly responsible for the increase of surface run-off, lowering ground water level and creating thermal heat island. Minimizing these problems, porous concrete is found one of the suitable pavement materials. Our main objective is developing geopolymer (fly ash + alkaline activator) based pervious concrete by adjusting mix-proportions so that the porosity remains within 15% to 25% and gives satisfactory strength.

1.3 Scope of work

Global warming effect or environmental temperature on earth surface is increasing for the various human activities. Cement industries are very much responsible for the rising of temperature due to the emission of greenhouse gas such as CO_2. There is a scope of study of low calcium fly ash geopolymer in porous concrete preparation. As we know that the strength of concrete is decreased with the increase of porosity or voids content. So, the development of porous concrete has been studied. In our experimental programme on 'Geopolymer based Porous Concrete', a blend of coarse aggregate type I (pass through 12.5 mm sieve and retain on 10 mm sieve) and coarse aggregate type II (pass through 10 mm and retain on 4.75 mm) in equal proportion along with few sand (by weight of total coarse aggregate) is used as total aggregate to enhance the strength property of geopolymer based porous concrete. A modified process of mixing geopolymer binder has been adopted to make easy in field construction. Also, there has a scope of the study to examine the effects of different parameters like alkaline activator to fly ash ratio; aggregate to binder ratio on mechanical as well as on engineering properties of geopolymer based porous concrete.

Chapter 2

Literature Review

2.1 General

In this chapter, a detailed review of the literature on porous concrete has been made. At first, literature related to cement based porous concrete has been briefly discussed. It includes mainly the study of strength and porosity. Further, papers related to geopolymer based porous concrete have been presented.

2.2 Cement based porous concrete

In 1995, Nader Ghafoori et al [1] have studied cement based porous concrete by measuring the compressive strength, tensile strength and modulus of elasticity in the laboratory. Portland cement satisfied ASTM C150 and limestone based coarse aggregate of maximum nominal size 9.5 mm have been taken as the main raw materials for the preparation of porous concrete. The specific gravity of coarse aggregate has been reported as 2.38 in SSD condition and the volume of voids between adjacent coarse aggregates has been found 40.5%. A detail of mixture proportions of such concrete has been shown in **Table 2.1**. Here in **Table 2.2**, a detail of test results on such porous concrete specimens has been tabulated. It is noted that the density of such concrete specimens is varying within a range from 1600 kg/m^3 to 1800 kg/m^3. It is also noted that the specimens which have been compacted under the applied energy of 33 J/m^3 and by hand both are resulted the same compressive strength. However, a maximum compressive strength of 15.6 MPa and minimum of 11.3 MPa have been achieved by the specimens compacting manually whereas flexural strength and split tensile strength are varying from 16.5% to 22% and 10.8% to 14.4% of their 28 days compressive strength respectively (**Refer Table 2.2**). A graphical representation of the coefficient of air permeability and gravimetric air content has been made, which is shown in **Figure 2.1**. It is clearly visible that the coefficient of air permeability is increasing exponentially as increasing air voids in the porous concrete matrix (**Refer Figure 2.1**).

Table 2. 1 Mix proportion details of no fines concrete mixture

Agg/Cement ratio	Cement (kg/m^3)	Added water (kg/m^3)	w/c ratio
4.0:1	413	173.45	0.372
4.5:1	376	167.5	0.381
5.0:1	348	156.8	0.390
6.0:1	300	144.0	0.418

Table 2. 2 Test results of cement based porous concrete mixtures

Aggregate/Cement ratio	Compaction energy (J/m^3)	Comp. strength (MPa)	Split tensile (MPa)	Flexural strength (MPa)	Density (kg/m^3)
4:1	Hand compaction	15.6	1.7	3.0	1716
	13	11.3	1.5	2.2	1643
	33	15.6	1.8	3.0	1710
	66	20.7	2.2	3.2	1800
4.5:1	Hand compaction	13.6	1.7	2.6	1677
	13	10.3	1.4	2.1	1624
	33	13.2	1.6	2.6	1652
	66	16.3	1.9	3.1	1734
5:1	Hand compaction	12.4	1.6	2.5	1664
	13	09.0	1.3	2.0	1600
	33	12.3	1.6	2.6	1652
	66	14.8	1.7	2.9	1676
6:1	Hand compaction	11.3	1.6	2.1	1643
	13	8.60	1.2	1.7	1581
	33	11.1	1.6	2.1	1640
	66	14.0	1.6	2.6	1666

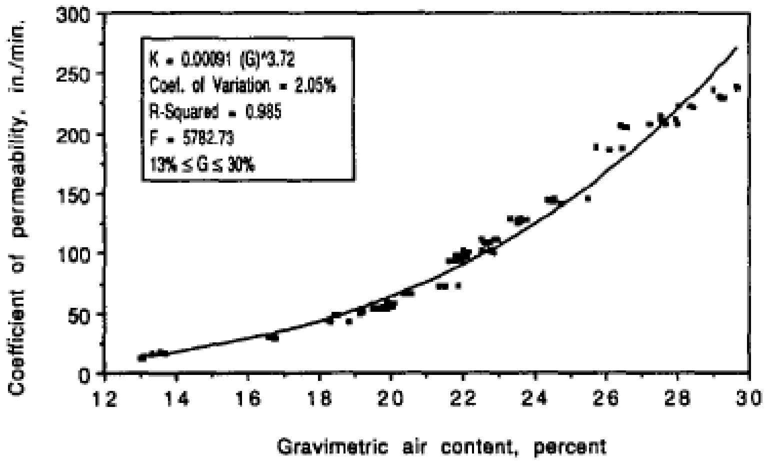

Figure 2. 1 Variation of the coefficient of permeability with gravimetric air content

Finally, the conclusions have been drawn as follows

1. With the increase of cement content, the density of cement base porous concrete increases and it is comparatively lower than the conventional cement based non-porous concrete.
2. The Compressive strength increases with the increase of cement to aggregate ratio as well as compaction effort.
3. Compaction effort has minimal effect on flexural as well as on split tensile strength.
4. The split tensile strength of porous concrete is slightly higher than that of conventional concrete.
5. The drying shrinkage value increases with the volume of cement paste. Therefore, it is lower than the conventional concrete. Average drying shrinkage value of such concrete has been found 0.00028 which is nearly half of conventional cement concrete.

In 2007, L. K. Crouch et al [2] have studied the effects of aggregates grading, amount and size on the strength of cement based porous concrete in the laboratory. It has been mentioned that proper selection of coarse aggregate is more effective than the high energy compaction method to reduce the volume of voids in porous concrete matrix. Therefore, four different samples have been prepared namely Mix A, B, C and D. Gradations of aggregate have been adjusted as per ASTM C136 using the coarse aggregate of maximum nominal size 9.5 mm and 12.5 mm. Even, to maintain a particular grade of aggregate a little amount of fine sand has been added with the coarse aggregate (**Refer Figure 2.2**). Mix A and Mix B have same cement-aggregate ratio but their aggregates gradation is different. Similar variation has been maintained for Mix C and Mix D. On the other hand, Mix B and Mix C have different cement to aggregate ratio but their aggregates gradation is the same. A detail of mixture proportions of such concrete mixtures has been presented in **Table 2.3**. However, by this experimental study, a maximum compressive strength of 31 MPa and minimum of 10 MPa have been achieved by such porous concrete specimens corresponding to their effective voids volume of 23% and 36% at 28 days (**Refer Figure 2.4, Figure 2.5** and **Figure 2.6**).

At the end, the conclusions have been made as follows

a. Proper aggregates gradation as used in Mix B should be maintain to enhance the strength properties of the porous concrete.
b. The compressive strength increases with the increase of cement to coarse aggregate ratio.
c. Uniformly graded aggregate is beneficial for the preparation of porous concrete, because it is difficult to achieve lesser voids even if the compaction effort is high.
d. Lower size coarse aggregates less than 12.5 mm increase the strength property.
e. The porous concrete mixture having effective air voids more than 31% shows unsatisfactory results. Thus, effective air voids up to 31% may be considered as the maximum limit to define porous concrete mixture functional (**Refer Figure 2.4 and Figure 2.6**).
f. Static modulus of elasticity could be enhanced by increasing cement content and using larger size coarse aggregate into the porous concrete mixture.

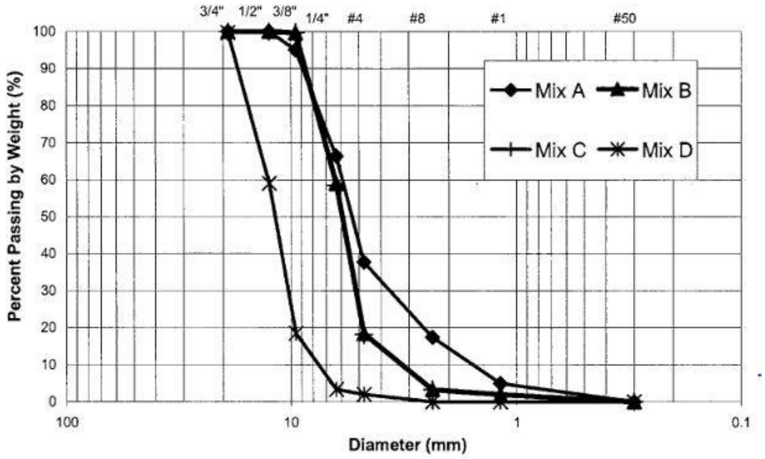

Figure 2. 2 Aggregates gradation plot

Table 2. 3 Porous concrete mixture proportions

Component	Mix A (kg/m^3)	Mix B (kg/m^3)	Mix C (kg/m^3)	Mix D (kg/m^3)
Cement	266.97	266.97	222.48	222.48
Fly ash	77.72	77.72	64.67	64.67
Water	105.01	105.01	87.21	87.21
Aggregate	1541.93	1541.93	1620.24	1620.24
Water/cement ratio	0.3	0.3	0.3	0.3
Cement/aggregate	4.5	4.5	5.6	5.6

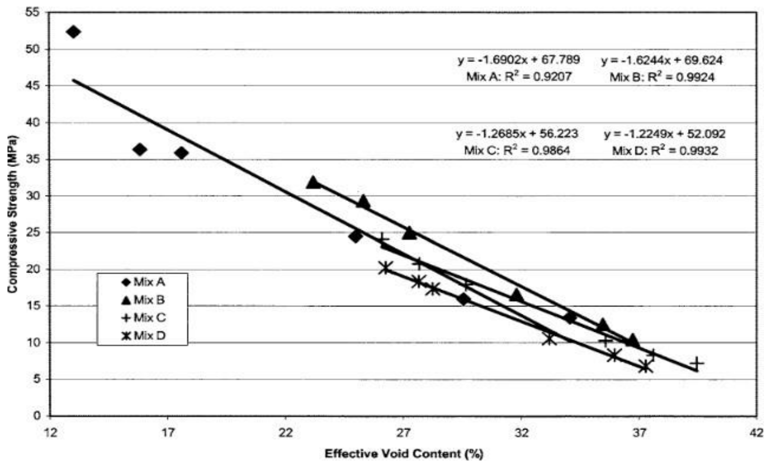

Figure 2. 3 Compressive strength vs effective void content plot

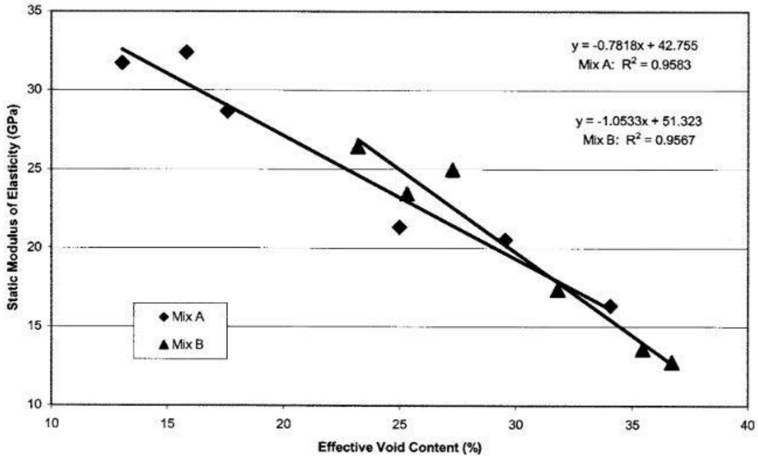

Figure 2. 4 Static modulus of elasticity vs effective void content- mixes A and B

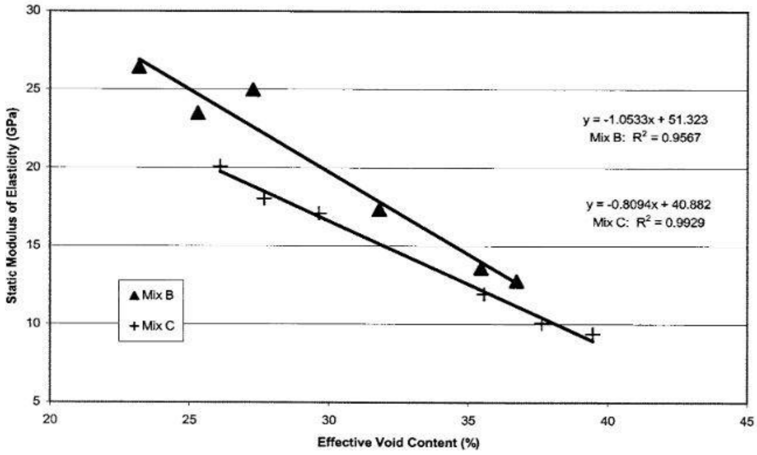

Figure 2. 5 Static modulus of elasticity vs effective void content—mixes B and C

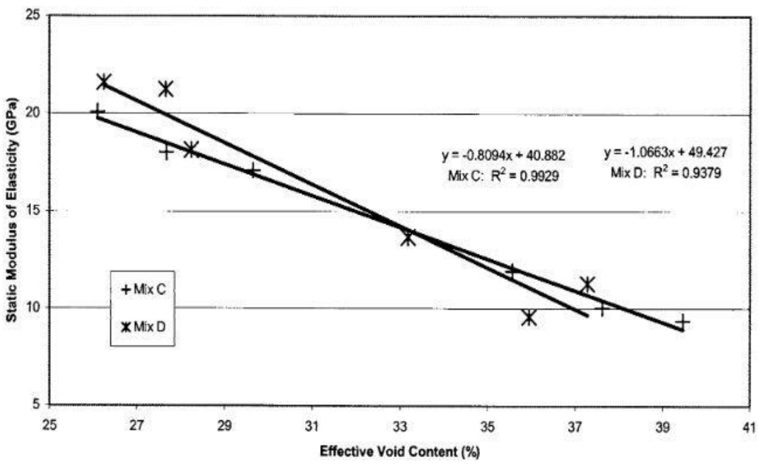

Figure 2. 6 Static modulus of elasticity vs effective void content—mixes C and D

In 2010, Omkar Deo et al [4] have discussed a method of characterizing the pore structure features of cement-based porous concrete material and predicted their coefficient of water permeability. They have measured pore sizes and porosity of several porous concrete specimens by volumetric and area fraction method. Mainly, Portland cement, three different single sizes coarse aggregates (i) pass through 12.5 mm sieve and retain on 9.5 mm sieve (ii) pass through 9.5 mm sieve and retain on 4.75 mm sieve (iii) pass through 4.75 mm sieve and retain on 2.36 mm sieve and their blend (mixing two of them in equal proportion by mass) have been taken for the preparation of porous concrete mixture. However, a detail of mixture proportions has been shown in **Table 2.4**.

The test results of porosity obtained from such concrete specimens have been shown in **Table 2.5** and **Figure 2.7**. It is clearly shown that there is no significant difference in porosity which has been obtained volumetrically and by the pore area fraction method. However, the porosity of such porous concrete specimens has been found within a range from 18% to 22%.

Table 2. 4 Detail of mixture proportions of the cement based porous concrete

Mix no	Cement (kg/m^3)	The maximum size of coarse Aggregate (kg/m^3)			Water (kg/m^3)	w/c ratio	Cement/Agg ratio
		4.75 mm	**9.5 mm**	**12.5 mm**			
I	312	1559	-	-	103	0.33	1:5
II	314	-	1568	-	104	0.33	1:5
III	312	-	-	1558	103	0.33	1:5
IV	305	776	776	-	101	0.33	1:5
V	309	773	-	773	102	0.33	1:5
VI	309	-	772	772	102	0.33	1:5

Table 2. 5 Measured volumetric porosity

Mix	Volumetric porosity (%)
I	20
II	19
III	20
IV	22
V	21
IV	21

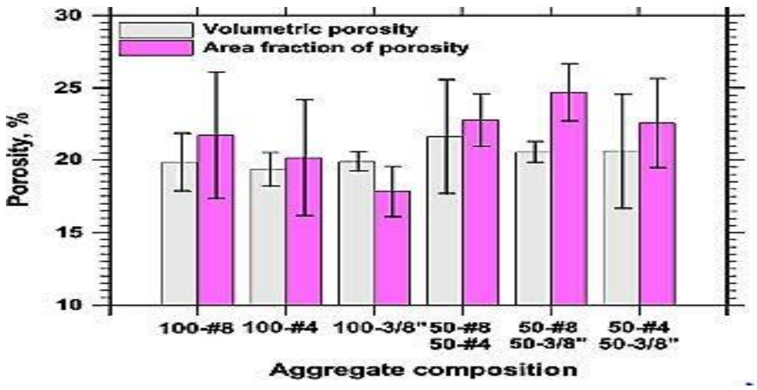

Figure 2. 7 Comparison of porosities of porous concretes measured by the pore area fraction and volumetric method

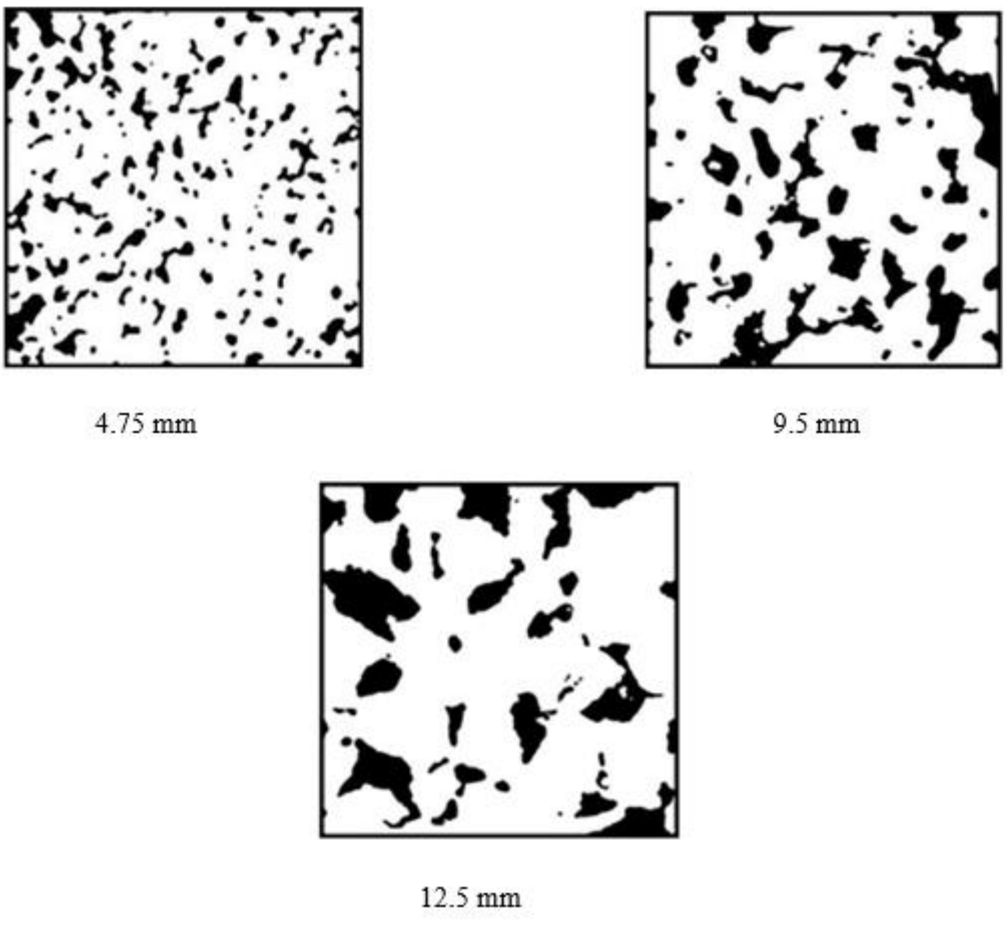

Figure 2. 8 Cross-sectional image of porous concrete specimens made off different single sizes coarse aggregates

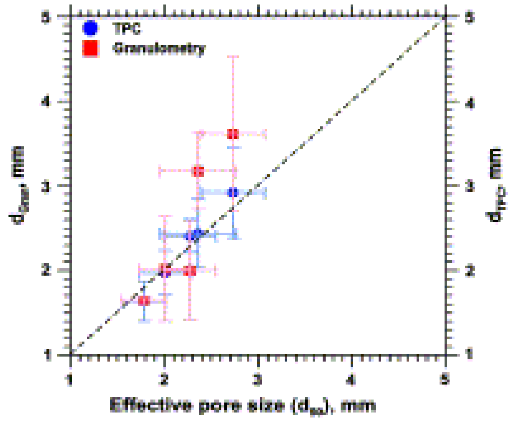

Figure 2. 9 Comparison of the pore sizes of porous concretes determined using different methods

At last, the following conclusions have been drawn from this study

- Using lower sized coarse aggregate of maximum nominal size 12.5 mm, it is possible to achieve porosity in the range of 18% to 22%.
- Average size of pores is varying from 2 mm to 4 mm but it has been found relatively large in case of blended aggregated porous concrete specimens. (**Refer Figure 2.9**)
- Both the volumetric and pore area fraction method are suitable for measuring the porosity.

In 2011, O. Deo et al [24] proposed a methodology of proportioning cement based porous concrete mixtures of the desired porosity. OPC type I, four different single sizes coarse aggregates such as (i). 4.75 mm (passing through 4.75 mm sieve, retained on 2.36 mm), ii) 9.5 mm (passing through 9.5mm sieve, retained on 4.75 mm), (iii) 12.5 mm (passing through 12.5 mm sieve, retained on 9.5 mm sieve), (iv) 20 mm (passing through 20 mm sieve, retained on 12.5 mm sieve) have been taken as the main raw materials for the preparation of porous concrete mixture. All such mixtures have been proportioned assuming three different levels of porosities such as 19%, 22%, and 27%. The designing methodology of such concrete material has been discussed here in short. Firstly, the required minimum volume of cement paste has been calculated as the volume of voids between adjacent coarse aggregate ($V_{\text{voids b/w coarse aggregate}}$) minus the desired porosity (ϕ_{design}).

$$V_{\text{p-min}} = V_{\text{voids b/w aggregate}} - \phi_{\text{design}}$$

Where $V_{\text{p-min}}$ = minimum volume of paste required

$V_{\text{voids between aggregates}}$ = total volume of inter-particle voids in coarse aggregates

Φ_{design} = desire porosity

Total volume of voids between adjacent coarse aggregate has been measured as per ASTM C29 (**Refer Figure 2.10**). After sample preparation, the specimens have been compacted as per ASTM C1688. In the first stage, porosity and unit weight of such porous concrete specimens have been measured and then a comparative study between design porosity and measured porosity has been made (**Refer Figure 2.11**). It is noted that the measured porosity values are 7% to 9% more than the design porosity values. Then, to fill the excess pores and meet the design porosity a concept of high and low paste contented mixture has been proposed. In case of highly-cemented porous concrete mixture, excess pores have been filled by the cement alone, but in case of low-cemented porous concrete mixture a percentage of excess pores (0.02 to 0.03) has been filled by cement and the remaining fraction has been filled by coarse aggregate. Here in **Table 2.6**, a detail of mixture proportions of such porous concrete mixtures has been tabulated. Finally, the porosity of such concrete specimens has been measured in both the fresh and hardened state, which also has been incorporated in **Table 2.6**. Eventually, it is found that the measured porosity is nearly the same as it has been designed. Based on the laboratory test results, stress-strain relationship and the variation of compressive strength with the porosity of such concrete specimens have been made, which have been shown in **Figure 2.12, Figure 2.13 and Figure 2.14** respectively. It is noted that the porous concrete specimens containing high amount of cement can withstand 30% more stress value than the low-cemented mixture (**Refer Figure 2.12 and 2.13**). However, by this method, a maximum compressive strength of 20 MPa has been achieved corresponding to their porosity value of 16% (**Refer Figure 2.14)**

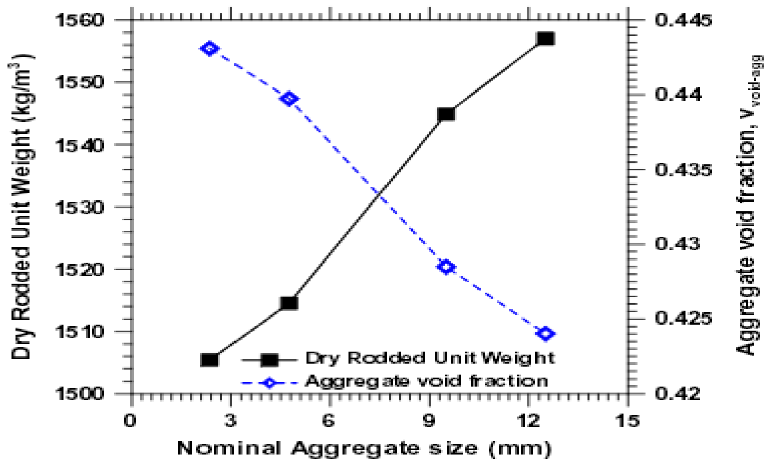

Figure 2. 10 Variation of dry rodded unit weight and aggregates void content of different nominal sized aggregate as per ASTM C 29

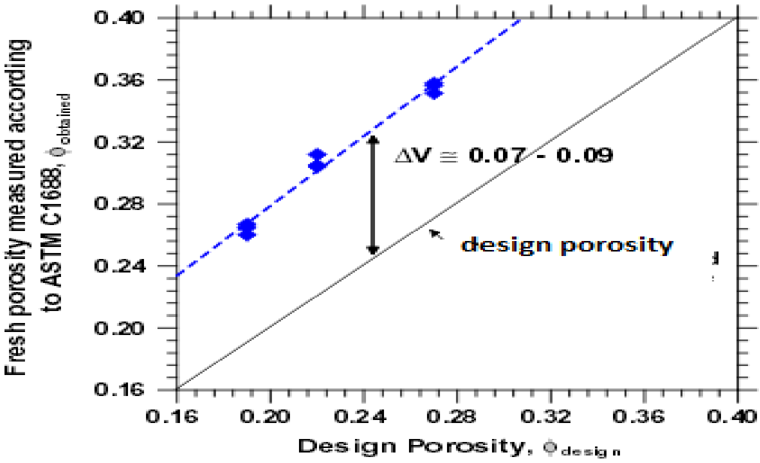

Figure 2. 11 Comparison between the design porosities and actual porosities (determined in accordance with ASTM C1688)

Table 2. 6 Mix proportions detail and their porosity in fresh and hardened state of cement based porous concrete

Mixture ID	Φ design	Cement (kg/m^3)	Water (kg/m^3)	CA (kg/m^3)	CA/cement ratio	w/c ratio	ϕ fresh	Φ hardened
high paste content mix								
100% 4.75 mm	0.19	554	180	1263	2.28	0.3	0.192	0.183
	0.22	496	163	1279	2.6	0.3	0.202	0.211
	0.27	411	137	1286	3	0.3	0.265	0.255
100% 9.5 mm	0.19	560	181	1253	2.2	0.3	0.196	0.169
	0.22	492	161	1285	2.6	0.3	0.219	0.223
	0.27	414	138	1281	3	0.3	0.261	0.256
100% 12.5 mm	0.19	539	175	1289	2.4	0.4	0.197	0.195
	0.22	485	160	1297	2.7	0.3	0.214	0.238
	0.27	398	133	1307	3.3	0.3	0.268	0.246
100% 20 mm	0.19	526	172	1310	2.5	0.3	0.186	0.164
	0.22	477	152	1311	2.7	0.3	0.221	0.245
	0.27	407	136	1293	3.2	0.3	0.278	0.261
low paste content mix								
100% 4.75 mm	0.22	317	101	1579	5.0	0.3	0.235	0.202
100% 9.5 mm	0.19	345	109	1612	4.6	0.3	0.196	0.195
	0.22	297	95	1634	5.5	0.3	0.233	0.242
	0.27	216	71	1652	7.6	0.3	0.272	0.289
100% 12.5 mm	0.19	336	107	1628	4.8	0.3	0.195	0.178
	0.22	287	92	1647	5.7	0.3	0.211	0.242
	0.27	206	68	1683	8.1	0.3	0.271	0.264

Φ is the porosity in %

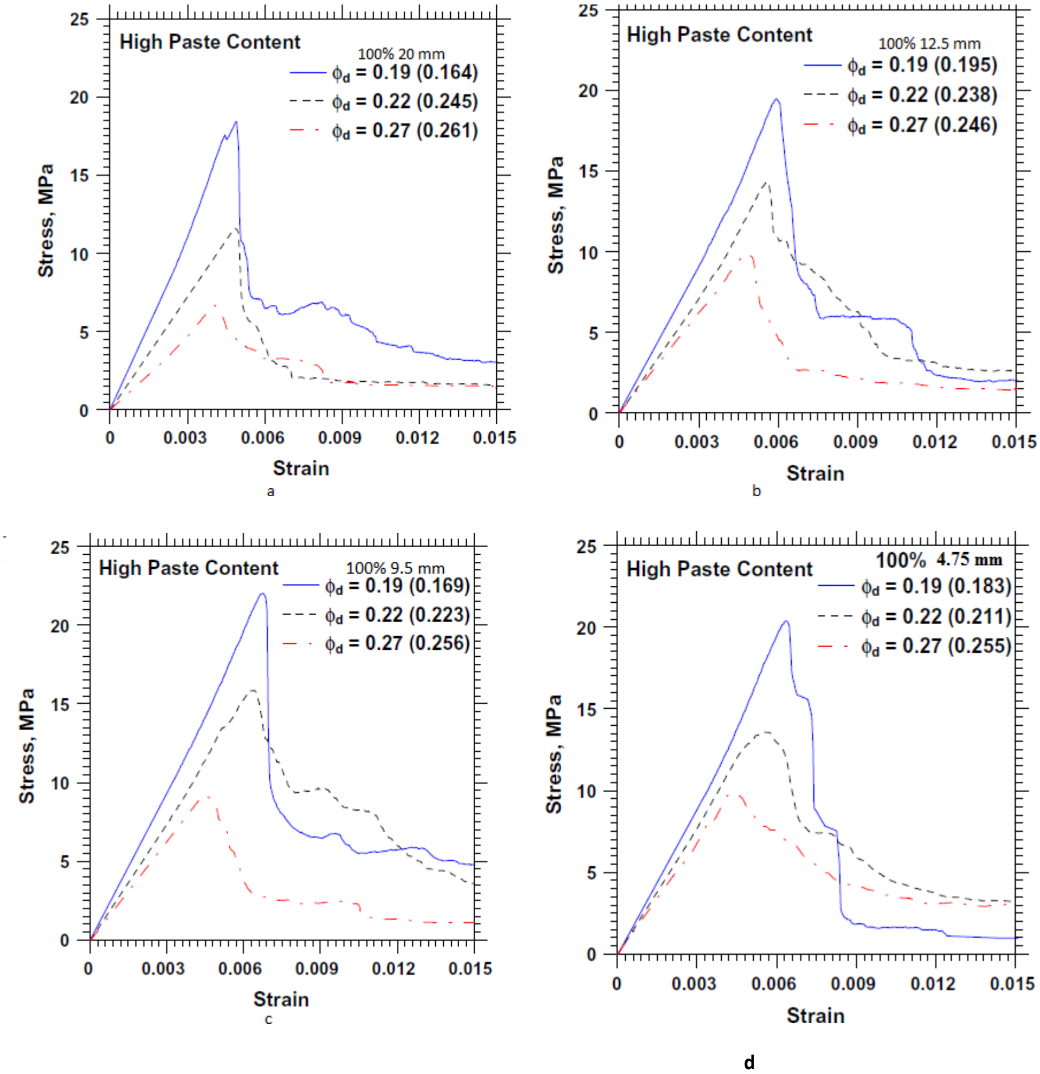

Figure 2. 12 Stress-strain relationship of high paste contented porous concrete mixture

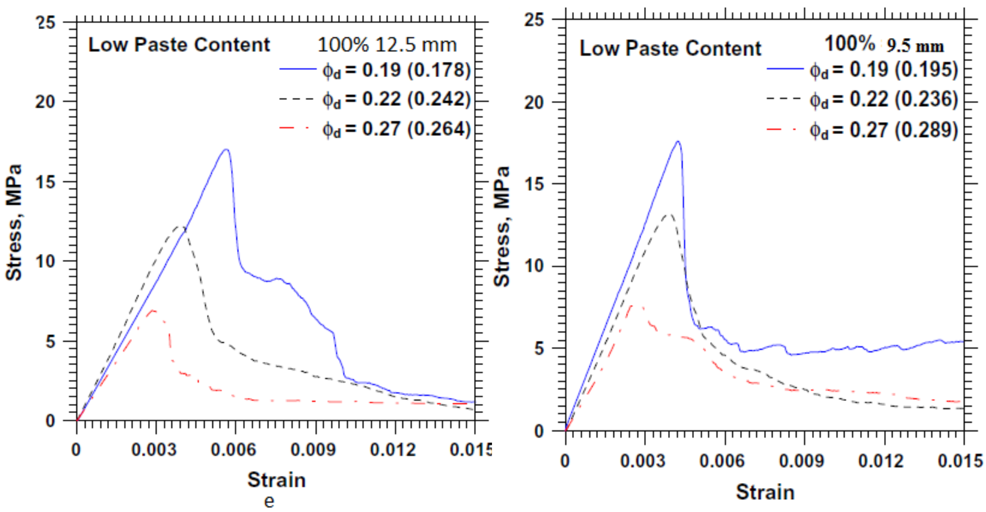

Figure 2. 13 Stress-strain relationship for the low paste contented porous concrete mixture

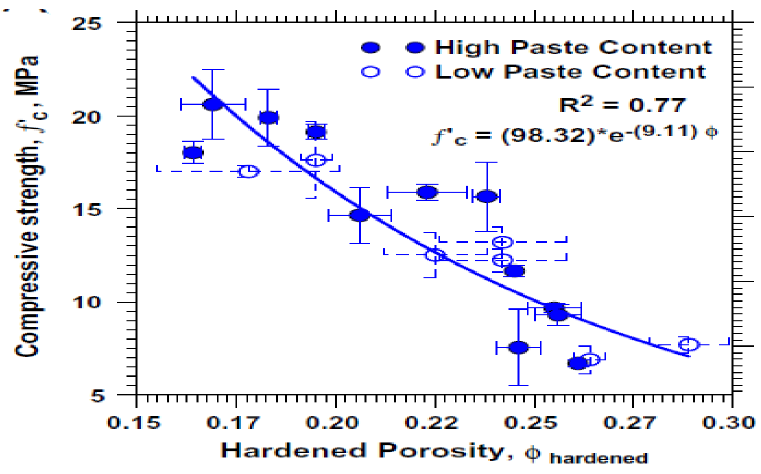

Figure 2. 14 Compressive strength vs porosity relationship of porous concrete

Finally, it is concluded that the proposed methodology can be adopted for the preparation of porous concrete materials.

In 2010, B. Hung et al [25] have examined the effect of latex, sand and fiber on the engineering properties of cement based porous concrete material in the laboratory. Portland cement, three different single sizes coarse aggregate (12.5 mm, 9.5 mm and 4.75 mm) have been taken as the main raw materials for the preparation porous concrete mixture. To enhance the strength and pore properties of porous concrete, some amount of latex, sand and fiber have been added in different combination. Physical properties of coarse aggregate have been shown in **Table 2.7**. A detail of mixture proportions of such porous concrete mixtures without sand in **Table 2.8** and with sand in **Table 2.9** have been presented. Here in **Figure 2.15** and **Figure 2.16** show the effect of latex, sand and fiber on the compressive strength and tensile strength of porous concrete respectively. It is notable that both the latex and sand are individually responsible for giving higher compressive strength but there are no significant effects of them on flexural strength as well as on porosity.

Finally, it is concluded that the strength property of porous concrete could be improved using smaller sized coarse aggregates less than 12.5 mm, little amount sand and latex without changing the porosity of porous concrete significantly (**Refer Figure 2.16**).

Table 2. 7 Properties of coarse aggregates

Aggregates size (mm)	Bulk Sp. Gravity	Apparent Sp. Gravity	Absorption (%)	Void content (%)
12.5	2.759	2.797	0.48	40
9.50	2.758	2.801	0.56	43
4.75	2.760	2.811	0.66	41

Table 2. 8 Detail of mixture proportions of cement based porous without sand

Agg/cement ratio	Agg. Size	Mix type	Cement (kg/m³)	Latex (kg/m³)	CA (kg/m³)	Water (kg/m³)	Fiber (kg/m³)	w/c ratio
4.5:1	12.5	A	320.2	-	1440.8	112.1	-	0.35
		B	314.8	31.5	1416.6	93.6	-	0.30
		C	320.2	-	1440.8	112.1	0.9	0.35
		D	314.8	31.5	1416.6	93.6	0.9	0.30
	9.5	A	320.4	-	1486.9	115.6	-	0.36
		B	324.9	32.5	1461.9	96.6	-	0.30
		C	320.4	-	1486.9	115.6	0.9	0.35
		D	324.9	32.5	1461.9	96.6	0.9	0.30
	4.75	A	352.6	-	1586.9	123.4	-	0.35
		B	346.7	34.7	1560.3	103.1	-	0.30
		C	352.2	34.7	1586.9	123.4	0.9	0.35
		D	346.7	-	1560.3	103.1	0.9	0.30

Table 2. 9 Detail of mixture proportions of cement based porous concrete with sand

Cement/Agg ratio	Agg. size	Mix type	Cement (kg/m³)	Latex (kg/m³)	CA (kg/m³)	Sand (kg/m³)	Water (kg/m³)	Fiber (kg/m³)	w/c ratio
4.5:1	12.5	A	300.6	-	1352.6	94.7	105.2	-	0.35
		B	295.8	29.6	1331.0	93.2	87.9	-	0.30
		C	300.6	-	1352.6	94.7	105.2	0.9	0.35
		D	295.8	29.6	1331.0	93.2	87.9	0.9	0.30
	9.5	A	311.9	-	1403.6	98.3	109.2	-	0.36
		B	306.9	30.7	1381.2	96.7	91.3	-	0.30
		C	311.9		1403.6	98.3	109.2	0.9	0.35
		D	306.9	30.7	1381.2	96.7	91.3	0.9	0.30
	4.75	A	329.8	-	1483.9	103.9	115.4	-	0.35
		B	324.5	32.5	1460.3	102.2	96.5	-	0.30
		C	329.8	-	1483.9	103.9	115.4	0.9	0.35
		D	324.5	32.5	1460.3	102.2	96.5	0.9	0.30

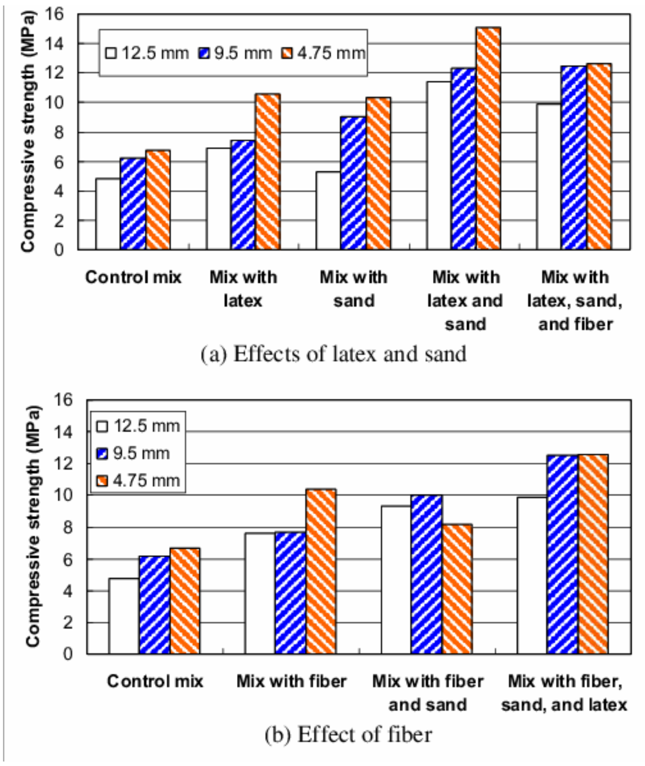

Figure 2. 15 Effect of latex, sand, and fiber on the compressive strength of cement based porous concrete

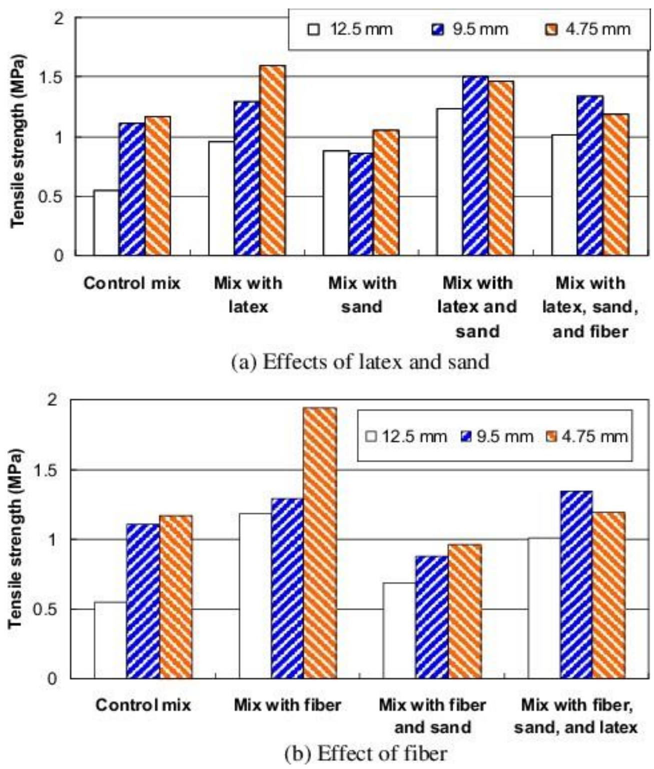

Figure 2. 16 Effect of latex, sand, and fiber on tensile strength of cement based porous concrete

In 2014, A. Yahia et al [23] have studied the effects of aggregates size, gradation and volume of paste on the strength and pore properties of cement based porous concrete mixtures. Portland cement, three different sizes coarse aggregate (i) CA10 (pass through 10 mm sieve and retain on 2.5 mm sieve) (ii) CA14 (pass through 14 mm sieve and retain on 5 mm sieve) (iii) CA20 (pass through 20 mm sieve and retain on 10 mm sieve) have been taken as the main raw materials for the preparation of porous concrete material. Physical properties of coarse aggregate have been shown in **Table 2.10**. However, in this experimental study, different samples of porous concrete have been prepared by keeping a fixed water to cement ratio of 0.3 and changing the ratio of paste-volume (PV) to the inter-particle voids volume (IPV) from 0.3 to 0.8. Mainly, the compressive strength, tensile strength, porosity and coefficient of water permeability have been measured. Here, in **Figure 2.17** change of porosity with different PV/IPV ratio and in **Figure 2.18** variation of the compressive strength and coefficient of water permeability with porosity have been shown. It is noted that the porosity is decreasing linearly with the PV/IPV ratio and PV/IPV percentages lower than 60% is providing functional porous concrete mixtures with a minimum porosity of 19% (**Refer Figure 2.17**). On the other hand, with the increase of porosity, coefficient of water permeability is increasing exponentially but 28 days compressive strength is decreasing linearly. It is also noted that some porous concrete mixtures with porosity 19% give minimum required water permeability coefficient of 1mm/sec and 28 days compressive strength of 22 MPa (**Refer Figure 2.18**). Here in **Figure 2.20** and **Figure 2.21** the variation of the compressive strength and in **Figure 2.22** and **Figure 2.23** the variation of the tensile strength with different PV/IPV ratio have been shown. It is noted that both the compressive strength and tensile strength are increasing with the increasing of PV/IPV ratio.

Finally, the following statements have been made as follows

- To make a cement based functional porous concrete mixture PV/IPV ratio should be maintained within a range from 0.3 to 0.6 but 0.5 shows the optimum results.
- A minimum porosity of 19% is required to get water permeability value of 1mm/sec in cold weather condition.
- The density of functional porous concrete is varied from 1800 kg/m^3 to 2100 kg/m^3 (**Refer Figure 2.19**).
- The compressive strength increases with the increase of PV/IPV ratio.
- The tensile strength of cement based porous concrete also increases with the increase of PV/IPV ratio.

Table 2. 10 Physical property of coarse aggregate measured as per ASTM C 29

Property	single size CA			Binary combination		
	CA10	CA14	CA20	1/2CA10+1/2CA14	3/4CA14+1/4CA20	1/4CA14+3/4CA20
Sp. Gravity in SSD cond.	2.73	2.74	2.77	2.74	2.76	2.75
Water Absorption (%)	0.34	0.43	0.39	0.39	0.4	0.42
Uc	1.81	1.92	1.2	1.72	3.33	2.17
Cc	1.03	0.9	0.95	0.8	0.93	1.84
Inter-particle voids volume (%)	42.5	41.7	43.2	41.8	41.7	40.2

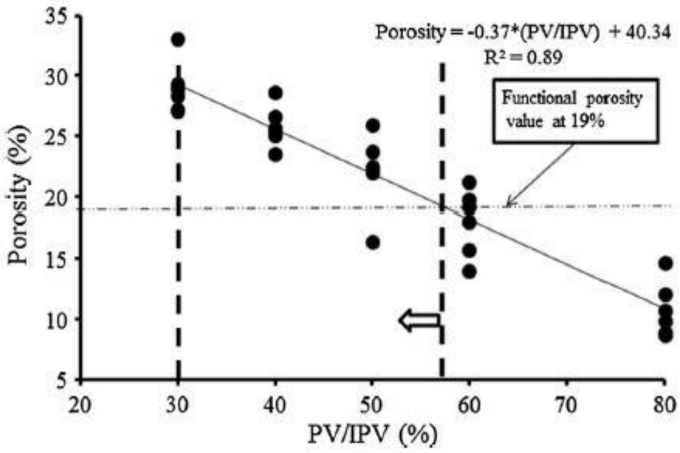

Figure 2. 17 Relationship between porosity and PV/IPV ratio

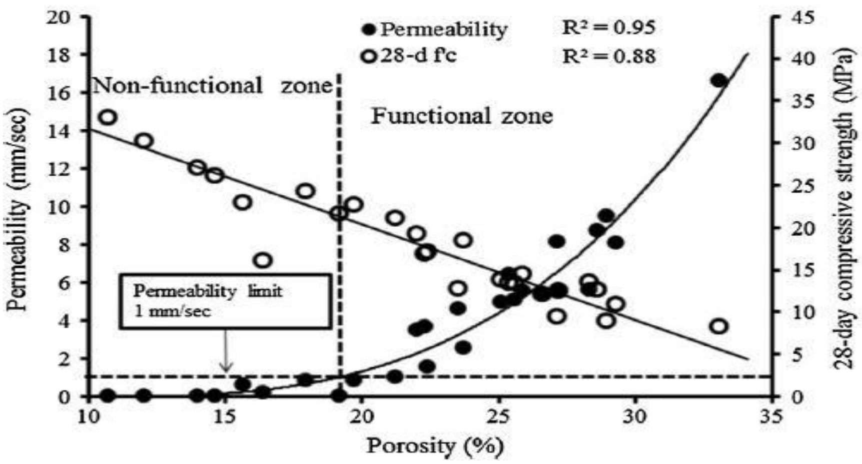

Figure 2. 18 Variation of the water permeability and compressive strength with porosity

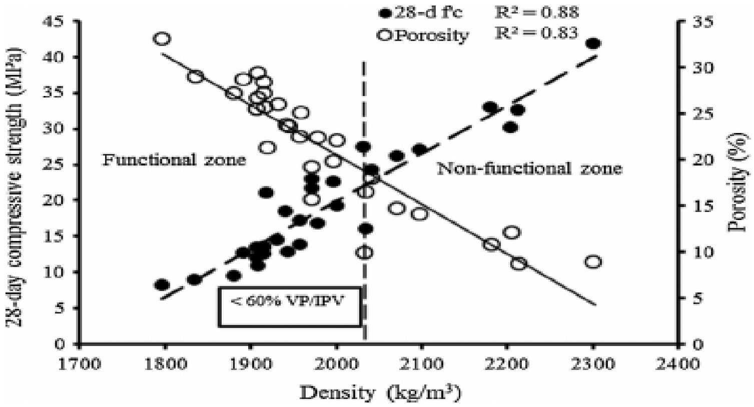

Figure 2. 19 28 days compressive strength and porosity vs density relationship

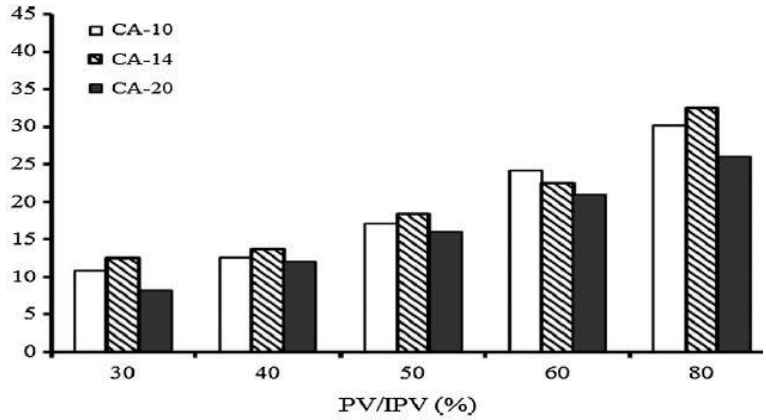

Figure 2. 20 Variation of 28 days compressive strength with PV/IPV ratios of single size aggregated cement based no fines concrete

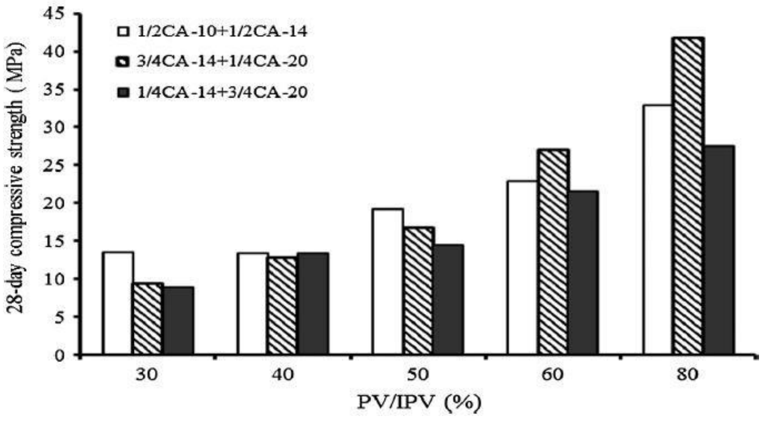

Figure 2. 21 Variation of the compressive strength with different PV/IPV ratios of blended aggregated cement based no fines concrete

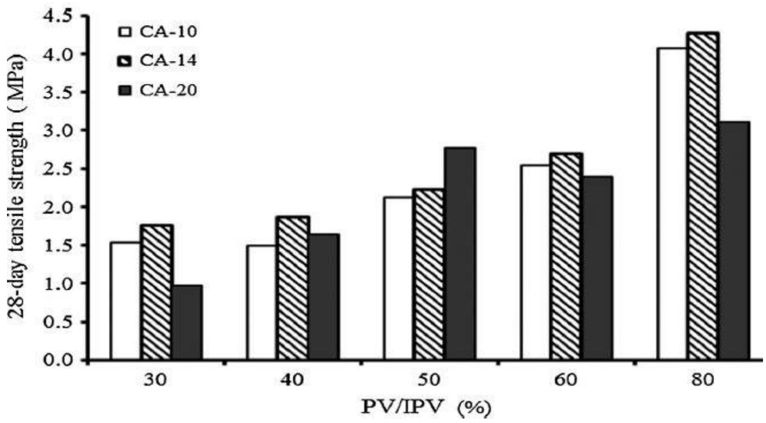

Figure 2. 22 Variation of tensile strength with different PV/IPV ratios of single size aggregated cement based no fines concrete

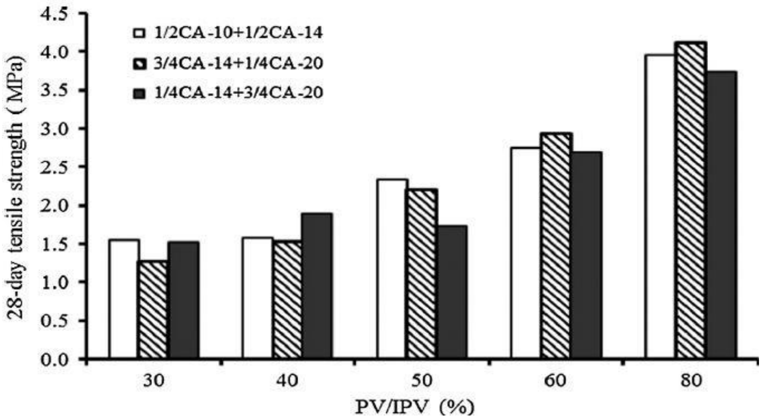

Figure 2. 23 Variation of tensile strength with different PV/IPV ratios of blended aggregated cement based no fines concrete

2.3 Geopolymer based concrete

In 2004, H. Harmurth et al [27] have investigated on geopolymer binder and discussed the effect of temperature on the strength property by storing the geipolymer binding specimens under water and ambient temperature condition after treating at different elevated temperature. The Geopolymer binder has been made from commercially available metakaolin containing 54.5% SiO_2 and 39.5% Al_2O_3 by mixing with Sodium based alkaline activator solution. The alkaline activator solution has been prepared by mixing Sodium hydroxide solution and water glass solution with silica modulus 3.38 together one day prior to use.

Table 2. 11 Compressive strength development under different curing condition of geopolymer binder

t(h) / T(^{0}C)	7 days compressive strength (MPa)						28 days compressive strength (MPa)					
	ambient conditions			under water			ambient condition			under water		
	60	75	90	60	75	90	60	75	90	60	75	90
2	31.3	28.9	30.3	31.1	22.3	31.4	37.8	29.4	36.9	34.4	18.4	25.1
4	30.6	34	32.1	25	28.8	19.9	34.3	39.8	32.8	28.7	28.4	26.7

The results of compressive strength (at 7 and 28 days) of the geopolymer binder in different curing condition has been presented here **(Refer Table 2.11)**. It is noted that the specimens which have been cured at an elevated temperature of 60^{0}C in a heat-controlled oven for 2 hours gives satisfactory compressive strength. However, the 7 days compressive strength is varying within a range from 80% to 92% of their 28 days compressive strength. From the above study it is concluded that (**i**) a heat treatment process is necessary for geopolymer binding material to gain early strength (**ii**) geopolymer binder gives higher early strength due to heat treatment than the cement binder even after storing the specimens under ambient temperature condition.

In 2005, P. Duxson et al [16] have studied the effect of Si to Al ratio on the engineering property of geopolymer gel in the laboratory. Commercially available metakaolin, sodium hydroxide pellet and sodium silicate solution have been taken for the preparation of geopolymer binder. To investigate the effect of Si/Al ratio on the compressive strength and Young's modulus, different samples of geopolymer binder have been prepared with varying Si to Al ratio from 1.15 to 2.15. However, based on test result, the variation of compressive strength and Young's modulus with Si/Al ratio has been presented in **Figure 2.24**. It is clearly visible that both the compressive strength and Young's modulus are increasing linearly as increasing Si/Al ratio from 1.15 to 1.9 and then decreasing due to further increase of Si/Ai ratio from 1.9 to 2.15.

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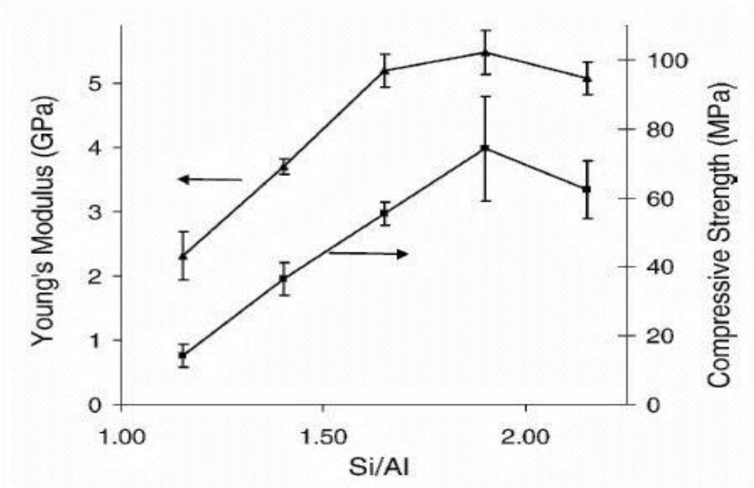
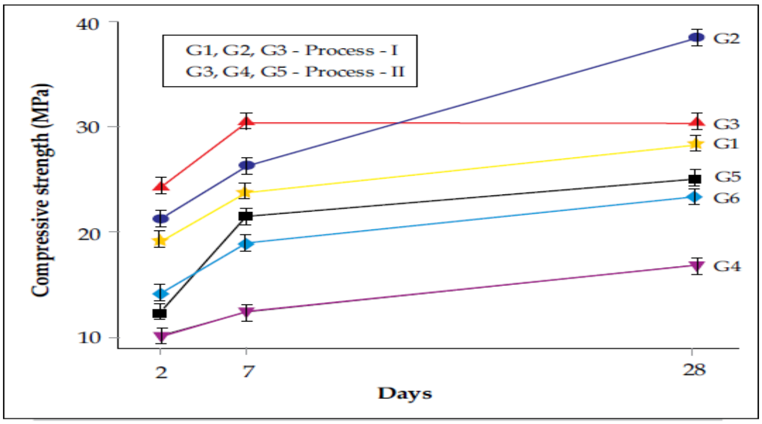


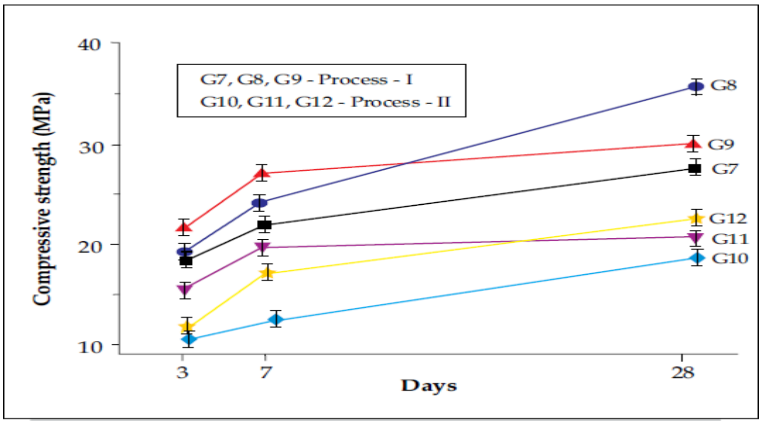
Figure 2. 24 Variation of the compressive strength and Young's modulus with Si/Al ratio of geopolymer binder

At last, it has been concluded that the compressive strength can be enhanced by maintaining optimum Si to Al ratio in the geopolymer binder.

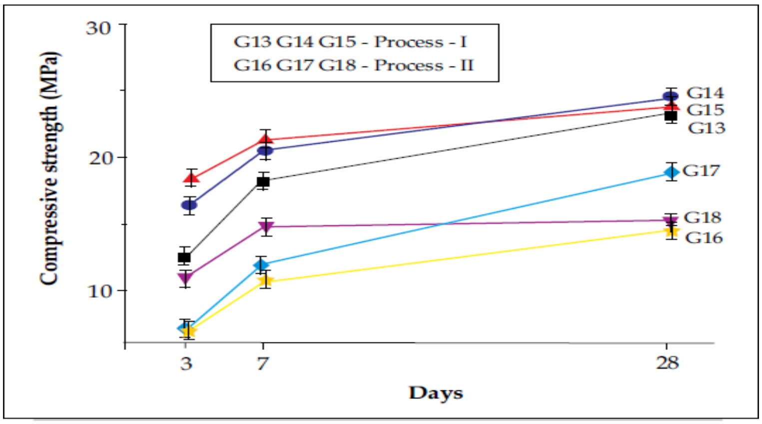
In 2015, D. Adak and S. Mandal [28] have proposed a new modified method of activating geopolymer binder. Low calcium class F fly ash (ASTM 2001), sodium hydroxide pellet (99% pure), sodium silicate solution (45% solids) and sand have been taken as the main ingredients for the preparation of geopolymer mortar. To study the effectiveness of the newly modified method, some samples of geopolymer mortar have been prepared by both the Process-I and Process-II and studied their strength property in the laboratory. Here, Process-I is the newly modified method whereas Process-II is the traditional method of casting geopolymer binding material. However, Process-I is our main concern which have been discussed here in short. At first, by mixing sodium hydroxide solution and sodium silicate solution at a fixed ratio of 1.75 by mass, alkaline activator solution has been prepared 24 hours before the sample preparation. Then, fly ash and alkaline activator solution have been mixed thoroughly and heated at different level of elevated temperature (40^0C, 60^0C and 80^0C) for 45 minutes to form a paste. After polymerization for a period, sand and the paste have been mixed in a pan properly and the mortar have been cast in mold. After casting, the entire specimens have been stored under ambient temperature condition (27 ± 2^0C, R.H 65%) till testing. Mainly, the compressive strength, flexural strength and split tensile strength have been measured in the laboratory. Based on the results, the variation of compressive strength with age of such concrete mortar have been shown in **Figure 2.25**. On the other hand, the variation of flexural strength and split tensile strength have been shown in **Figure 2.26** and **Figure 2.27** respectively. It is evident that the specimens that have been made by process-I at an elevated temperature of 60^0C give satisfactory and higher compressive strength.



a

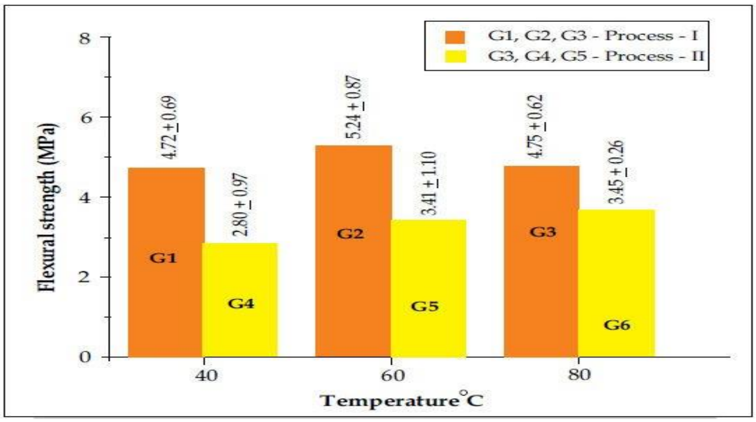


b



c

Figure 2. 25 Variation of compressive strength with age of geopolymer mortar in process-I and II, maintain alkaline activator to fly ash ratio a) 0.35 b) 0.40 and c) 0.45



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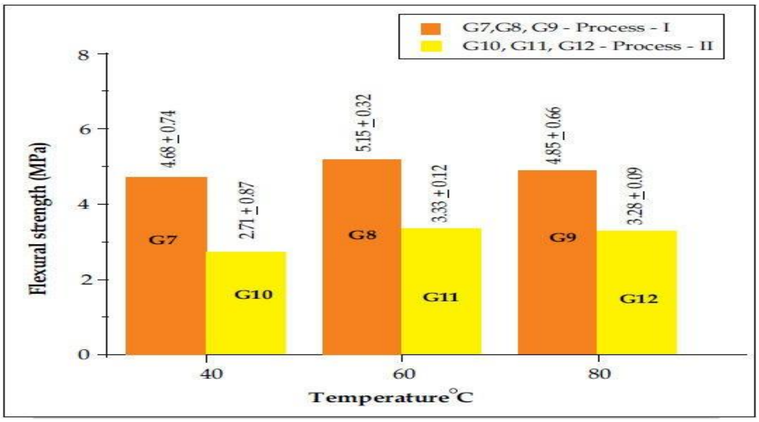

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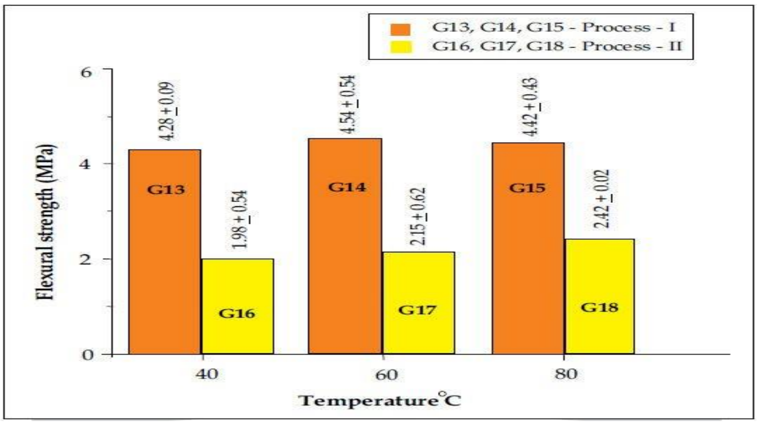
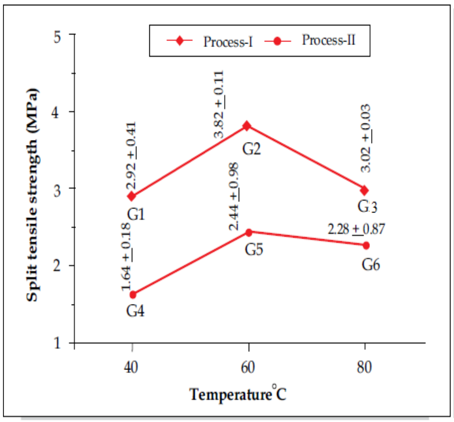
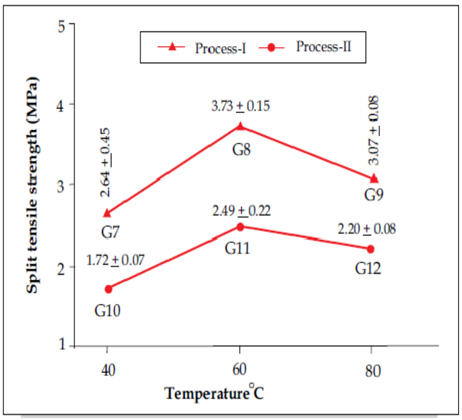


c

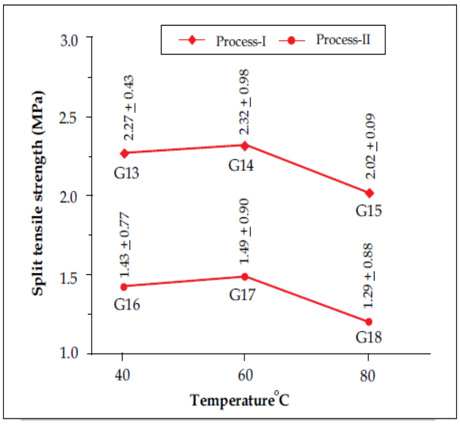
Figure 2. 26 Variation of flexural strength of geopolymer mortar with curing temperature in the process I & II, maintain alkaline activator/ fly ash ratio a) 0.35 b). 0.40 c) 0.45



alkaline activator/ flash ratio **0.35**



alkaline activator/fly ash **0.40**



alkaline activator/fly ash **0.45**

Figure 2. 27 Split tensile strength of different geopolymer mortar

Thus, from the above study, it has been concluded that (**i**) the newly modified method (**Process-I**) is more effective and suitable for field construction of geopolymer binding material than the traditional method (**Process-II**). (**ii**) Low calcium fly ash can be used to make a good quality of geopolymer binding material.

In 2004, D. Hardjito, B.V. Rangan et al [29] have studied the effect of different variables such as age, curing duration, curing temperature, quantity of superplasticizer and amount of water content mainly on the compressive strength of geopolymer concrete. Class F fly ash and Sodium based alkaline activator have been taken for the preparation of geopolymer binder. The chemical composition of fly ash is shown in **Table 2.12**. The variation of the compressive strength with curing duration and aging have been shown in **Figure 2.28** and **Figure 2.29**. It is noted that the compressive strength is increasing with curing duration but there is no significant increase in compressive strength after 7 days of aging. **Figure 2.30** and **Figure 2.31** show the variations of the compressive strength with molar H_2O to Na_2O ratio and H_2O

to geopolymer solid ratio. It is evident that the compressive strength is increasing as decreasing H_2O to Na_2O ratio and H_2O to geopolymer solid ratio.

Finally, the conclusions have been made as follows

- The compressive strength of geopolymer concrete is increased with the decrease of molar H_2O to Na_2O ratio and water to geopolymer solid ratio.
- Naphthalene based superplasticizer more than 2% into the geopolymer based porous concrete decreases the compressive strength.
- Geo-polymerization within an elevated temperature from 600C to 750C gives satisfactory compressive strength.

Table 2. 12 Chemical composition of fly ash in percentage

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	LOI
53.36	26.49	10.86	1.34	0.37	0.8	1.47	0.77	1.43	1.7	1.39

Table 2. 13 Detail of alkali activating solution and curing process of mixture

Molar concentration in NaOH solution	8M	14M
Na_2SiO_3/NaOH soln. ratio	2.5	2.5
Curing time	24 hours	24 hours
Curing temperature	60˚C	30˚C, 45˚C, 75˚C, 90˚C

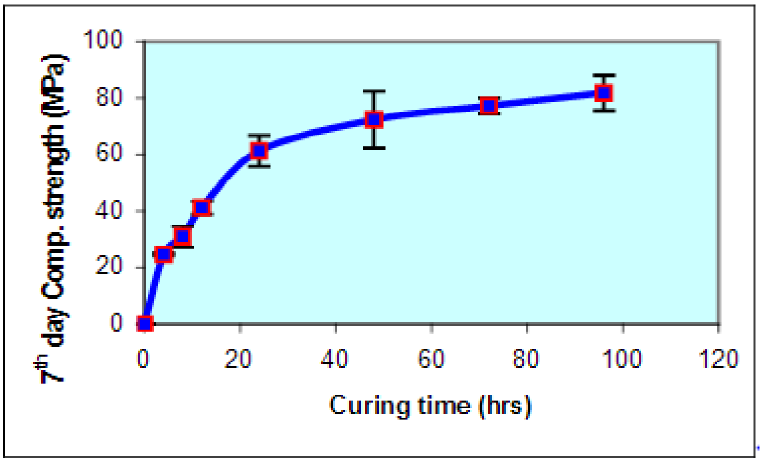


Figure 2. 28 Variation of the compressive strength with age of curing of geopolymer concrete

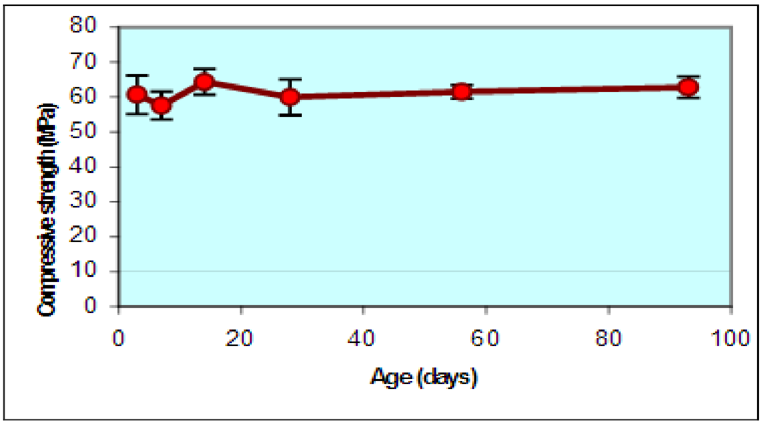


Figure 2. 29 Compressive strength at different age of geopolymer concrete

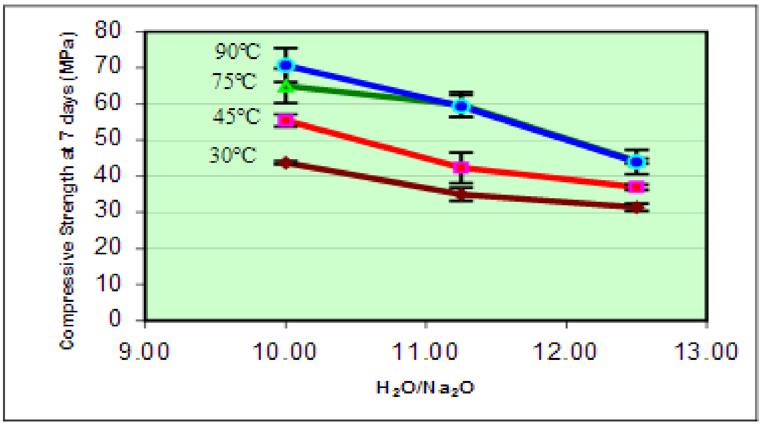


Figure 2. 30 Effect of molar H_2O to Na_2O ratio on compressive strength of geopolymer concrete

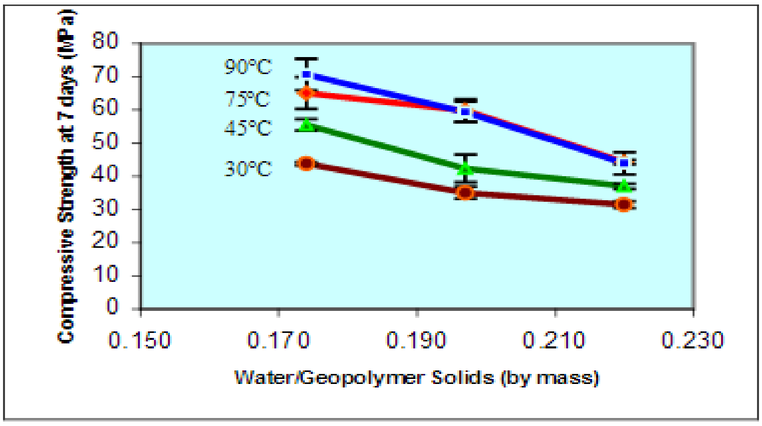


Figure 2. 31 Effect of water to geopolymer solids ratio on compressive strength of geopolymer concrete

In 2011, M. Olivia et al [8] have studied the effects of different parameters such as grading of aggregate, fly ash content, water to geopolymer solid ratio and aggregate to geopolymer solid ratio on the strength and water penetrability properties of geopolymer concrete material. Low calcium class F fly ash (ASTM C618), three different single sizes coarse aggregate (7 mm, 10 mm and 20 mm), 14M sodium hydroxide solution and sodium silicate solution (Na_2O =14.7%, SiO_2 =29.4%) have been taken for the preparation of geopolymer concrete. Chemical composition of fly ash has been shown in **Table 2.14**. To investigate the effects of such parameters, some samples of geopolymer concrete have been prepared and their compressive strength, water absorption and coefficient of water permeability have been measured in the laboratory. However, a detail of mixture proportions of such concrete material has been shown in **Table 2.15**. **Figure 2.32** shows the average compressive strength of geopolymer concrete at 7, 28 and 91 days. It is noted that the compressive strength of all mixtures is increasing with the age but there is insignificant gain in compressive strength after 7 days of aging. It is also noted that the compressive strength is increasing as decreasing water to geopolymer solids ratio, aggregate to geopolymer solids ratio and alkaline activator solution to fly ash ratio and gradation of aggregate has minimal effect on it. **Table 2.16** shows the average water permeability coefficients and the void content percentages of some selected geopolymer concrete mixtures. It is observed that the coefficient of water permeability has been found in order of 10^{-11} m/sec within a range of voids from 8.2% to 13%.

At last, the conclusions have been made as follows

a. The compressive strength of geopolymer concrete mixture increases with the decrease of water to solid ratio, aggregate to solid ratio, and aggregate to fly ash ratio. But, gradation of aggregate has minimal effect on compressive strength.
b. The coefficient of water permeability increases with the increase of volume of voids in concrete mixture.
c. There is no significant gain in compressive strength of geopolymer concrete after 7 days of aging.
d. The results indicate that low calcium fly ash can be used to make a good quality of concrete material.

Table 2. 14 Chemical composition of fly ash in percentage by mass

Oxides	% present in Fly ash
Silica (SiO_2)	50.50
Alumina (Al_2O_3)	26.57
Calcium Oxide (CaO)	02.13
Ferric Oxide (Fe_2O_3)	13.77
Potassium Oxide (K_2O)	0.77
Magnesium Oxide (MgO)	1.54
Sodium Oxide (Na_2O)	0.45
Phosphorous pent-oxide (P_2O_5)	1.00
Sulphuric anhydride (SO_3)	0.41
LOI	0.60

Table 2. 15 Detail of mixture proportions of geopolymer concrete

						coarse aggregate							
Mix No	FA/CA ratio	W/S ratio	CA/Solid ratio	AA/FA ratio	water	7mm	10mm	20mm	Sand	Fly ash	NaOH Sol^n (14M)	SS	SP
GP1	1:4.5	0.23	3.9	0.35	25.8	647	554	-	647	408	41	103	6
GP2	1:4.5	0.22	3.9	0.35	20.7	647	554	-	647	408	41	103	6
GP3	1:4.5	0.20	3.9	0.35	16.5	647	554	-	647	408	41	103	6
GP4	1:4.0	0.22	3.5	0.35	25.8	630	540	-	630	444	44	111	6
GP5	1:5.4	0.24	4.7	0.35	25.8	672	576	-	672	356	36	89	6
GP6	1:4.4	0.23	3.9	0.30	25.8	647	554	-	647	424	3	91	6
GP7	1:4.8	0.23	3.9	0.45	25.8	647	554	-	647	381	49	122	6
GP8	1:4.5	0.23	3.9	0.35	25.8	645	370	277	554	408	41	103	6
GP9	1:4.5	0.23	3.9	0.35	25.8	-	924	370	554	408	41	103	6
Quantity (kg/m^3)													

Table 2. 16 Test results of water permeability and voids content of geopolymer concrete

Mixture No.	Water permeability (m/s)	Voids content (%)
GP1	4.67×10^{-11}	10.5
GP2	3.95×10^{-11}	13.0
GP3	2.46×10^{-11}	10.8
GP4	2.91×10^{-11}	10.0
GP8	2.61×10^{-11}	8.20

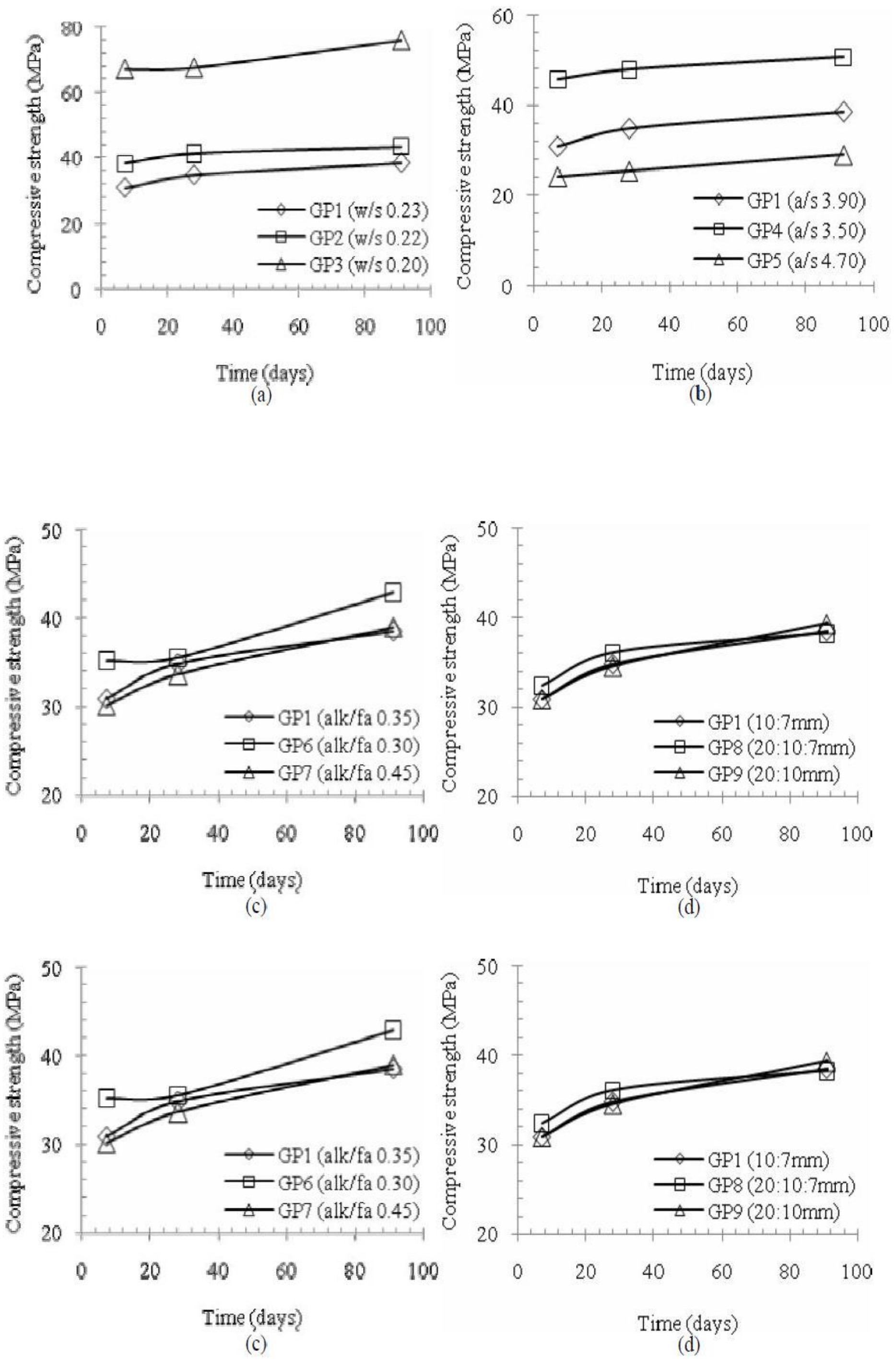


Figure 2. 32 Strength development of concrete with various parameters (a) water/solids ratio (b) aggregate/solids ratio (c) alkaline activator/fly ash ratio (d) aggregate grading; at 7, 28 and 91 days

In 2011, Vanchai Sata et al [31] have conducted a laboratory experimental study on geopolymer binding porous concrete. High calcium fly ash, sodium hydroxide solution (NH), sodium silicate solution with 15.32% Na_2O, 32.87% SiO_2 and 51.81% H_2O and crushed limestone coarse aggregate (pass through 20 mm sieve and retain on 12.5 mm sieve) have been used for the preparation of porous concrete. Chemical composition of fly ash has been shown in **Table 2.17**. To investigate the effects of alkaline activator to fly ash ratio, molar concentration in sodium hydroxide solution on the properties of PGC, three different alkaline activator solution to fly ash ratio of 0.35, 0.40 and 0.45 along with sodium hydroxide solution of 10M, 15M and 20M have been maintained whereas NS to NH solution ratio was 0.5 for all. However, a detail of mixture proportions of geopolymer based porous concrete has been shown in **Table 2.18**. After sample preparation, the porous concrete specimens have been cured at an elevated temperature of 60^0C for 48 hours and then stored in a controlled room temperature at $(23\pm2)^0$C, R.H 50% till testing. The compressive strength, split tensile strength, volume of voids and coefficient of water permeability of the geopolymer based porous concrete have been measured, which have been reported here in **Table 2.19**. From the above test results, it is noted that the compressive strength is increasing as decreasing the alkaline activator solution to fly ash ratio and increasing of molar concentration up to 15M. However, a maximum compressive strength of 11.4 MPa and the split tensile strength within a range from 10.4% to 16.7% has been found by such porous concrete specimens. On the other hand, the coefficient of water permeability has been found within a range from 1.92 cm/sec to 5.96 cm/sec corresponding to their volume of voids from 28.7% to 34.4%.

Finally, it has been concluded that (**i**) the compressive strength increases with the increase of molar concentration upto 15M. (**ii**) The compressive strength increases with the decrease of alkaline activator solution to fly ash ratio. (**iii**) Split tensile strength of geopolymer based porous concrete is slightly higher than that of cement based porous and non-porous concrete.

Table 2. 17 Chemical composition of fly ash used in sample preparation

SiO_2	Al_2O_3	Fe_2O_3	CaO
36.80%	15.20%	19.70%	19.40%

Table 2. 18 Detail of mixture proportions of geopolymer based porous concrete

Quantity in kg/m³			NaOH Solution				
Mix No	**Fly ash**	**Na_2SiO_3 soln**	**10M**	**15M**	**20M**	**CA**	**FA/A ratio**
35PGC10	221	25.5	51	-	-	1768	1:8
35PGC15	221	25.5	-	51	-	1768	1:8
35PGC20	221	25.5	-	-	51	1768	1:8
40PGC10	221	29.5	59	-	-	1768	1:8
40PGC15	221	29.5	-	59	-	1768	1:8
40PGC20	221	29.5	-	-	59	1768	1:8
45PGC10	221	33	66	-	-	1768	1:8
45PGC15	221	33	-	66	-	1768	1:8
45PGC20	221	33	-	-	66	1768	1:8

Table 2. 19 Test results of geopolymer based porous concrete

Mix	Voids content (%)	Water permeability (cm/sec)	Density (kg/m³)	Comp. strength (MPa)	Split tensile strength (MPa)
35PGC10	30.5	2.22	1780	8.5	1.0
35PGC15	30.9	3.61	1770	9.3	1.3
35PGC20	34.4	5.96	1680	5.4	0.7
40PGC10	30.7	2.66	1770	10.1	1.1
40PGC15	28.8	2.91	1820	9.9	1.3
40PGC20	31.8	3.96	1740	8.4	1.4
45PGC10	28.7	3.64	1810	10.2	1.1
45PGC15	28.7	1.92	1810	11.4	1.2
45PGC20	29.9	2.39	1780	9.6	1.2

In 2012, V. Sata et al [32] have investigated the performance of recycle coarse aggregate in geopolymer based porous concrete material. High calcium fly ash, sodium hydroxide solution (10M, 15M, and 20M), sodium silicate solution with 32.87% SiO_2, 15.32% Na_2O and 51.81% H_2O and two different types of recycle coarse aggregate (pass through 9.5 mm sieve and retain on 4.5 mm sieve) such as crushed structural concrete member (RC) and crushed clay brick (RB) have been taken for the laboratory experimental study. Mainly, the compressive strength, split tensile strength, void ratio and coefficient of water permeability of such porous concrete specimens have been measured. Literally, to compare the test results, some samples of geopolymer binding porous concrete have been prepared using limestone based natural coarse aggregate (NA). However, properties of coarse aggregate in **Table 2.20** and a detail of mixture proportioning of such porous concrete material in **Table 2.21** have been shown. After casting, all the specimens have been placed in a heat-controlled oven for 48 hours at an elevated temperature of 60^0C for heat treatment and then stored in a room temperature at $23^0 \pm 2^0$C and R.H 50% till testing. The test results obtained from such porous concrete specimens have been tabulated in **Table 2.22**. From the above test results, it is clearly visible that the density of recycle aggregated porous concrete is slightly lower than that of natural aggregated porous concrete because of high percentage of voids content in the recycle aggregated porous concrete (**Refer Table 2.22**). it is also noted that the compressive strength and split tensile strength of recycle aggregated porous concrete are comparatively less than that of natural aggregated porous concrete.

At the end, the following conclusions have been drawn (**i**) recycle aggregate could be used to make porous concrete material. (**ii**) Recycle aggregated concrete is comparatively light weighted than the normal aggregated concrete. (**iii**) The compressive strength of recycle aggregated concrete is approximately 25% less than that of normal aggregated concrete.

Table 2. 20 Properties of coarse aggregates

Aggregate	Sp. Gravity	Dry rodded density (kg/m³)	Water absorption (%)	Loss-Angeles abrasion loss (%)
NA	2.72	1590	0.21	30.2
RC	2.53	1340	4.58	43.3
RB	2.02	950	16.2	42.5

Table 2. 21 Mix proportions detail of both the normal and recycle aggregated geopolymer based porous concrete

Quantity in kg/m³			**NaOH solution**			**Coarse aggregate**			
Mixes	**FA**	**Na_2SiO_3 solⁿ**	**10M**	**15M**	**20M**	**NA**	**RC**	**RB**	**FA/CA ratio**
NA10	221	33	66	-	-	1768	-	-	1:8
NA15	221	33	-	66		1768	-	-	1:8
NA20	221	33	-	-	66	1768	-	-	1:8
RC10	221	33	66	-	-	-	1768	-	1:8
RC15	221	33	-	66	-	-	1768	-	1:8
RC20	221	33	-	-	66	-	1768	-	1:8
RB10	221	33	66	-	-	-	-	1768	1:8
RB15	221	33	-	66	-	-	-	1768	1:8
RB20	221	33	-	-	66	-	-	1768	1:8

Table 2. 22 Test results of normal and recycle aggregated geopolymer based porous concrete

Mix	Density (kg/m^3)	Comp. strength (MPa)	Split tensile Strength (MPa)	Voids (%)	Permeability (cm/sec)
NA10	1840	13.6	1.6	24.2	1.25
NA15	1760	13.6	1.8	25.3	1.18
NA20	1810	11.9	1.5	27.4	1.71
RC10	1730	07.0	1.3	26.8	1.56
RC15	1710	10.0	1.4	26.9	1.46
RC20	1720	10.3	1.5	26.4	1.47
RB10	1420	02.9	0.4	23.7	1.12
RB15	1510	04.0	0.7	21.7	0.71
RB20	1520	06.6	0.9	22.4	0.80

Chapter 3

Experimental Programme

3.1 General

This Chapter describes the detail of the present experimental work. First, the materials, mixture proportions, manufacturing, and curing of the test specimens are explained. This chapter is then discussed experimental parameters and testing procedure. Mix-design procedure of ‘Geopolymer based Porous Concrete’ is not the same as followed in conventional concrete. Conventional concrete is designed mainly based on strength requirement, but porous concrete mixtures are designed based on desire porosity or volume of voids. Here the entire mixtures are proportioned such that its porosity is to be within an optimum range of 15% to 25%.

3.2 Materials used

Low calcium class F (ASTM 2001) fly ash, Sodium based alkaline activator solution and locally available coarse aggregate have been used for the preparation of geopolymer based porous concrete material. A small quantity of sand passing through 4.75 mm sieve is also mixed to enhance the strength of the porous concrete mixture. No admixture has been added to any mixture.

Fly-ash: Low calcium class F (ASTM 2001) fly ash, collected from Farakka National Thermal Power Plant, West Bengal, was the main source material to prepare the geopolymer binder. Measured Specific gravity is 2.05. Grain size distribution and chemical analysis of fly ash are tabulated below **(Refer Table 3.1 and 3.2)**.

Table 3. 1 Grain size distribution of low calcium fly ash

Material	Particle size distribution						
Fly ash	> 500 µm	300-500 µm	150-300 µm	90-150 µm	45-90 µm	< 45µm	sp. Gravity
	NIL	1.42	11.67	48.06	31.98	6.87	2.05

Table 3. 2 Chemical composition of fly ash by mass in percentage

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_4	LOI
64.97%	26.64%	5.69%	0.33%	0.85%	0.49%	0.25%	0.33%	0.45%

Alkaline activator solution: A mix solution which is a combination of Sodium hydroxide and Sodium silicate solutions with an appropriate amount of extra water has been prepared to activate the source materials. Solid Sodium hydroxide pellets (99% pure) are mixed with laboratory tap water to make 12M sodium hydroxide solution. Sodium silicate solution contains 45% solid and highly viscous having the specific gravity of 1.53 g/cc. A constant Sodium silicate to Sodium hydroxide solution ratio of 1.75 has been maintained in the present mixture proportioning.

Coarse aggregates: In order to maintain sufficient pores and to enhance the strength properties a typical grade of coarse aggregates have been made which is a blend of two different single sized coarse aggregates of type I (pass through 12.5 mm and retain on 10 mm IS sieves) and type II (pass through 10 mm and retain on 4.75 mm IS sieve). Both the coarse aggregate type I and II are mixed in an equal proportion by mass of the total coarse aggregates. Measured specific gravity of coarse aggregate in SSD condition is 2.74.

3.3 Mixing, casting and curing procedures

As we know, the preparation of Geopolymer concrete is not the same as the traditional cement concrete. Though, the present laboratory mixing procedure is not similar as generally followed by many researchers for the preparation of geopolymer based porous concrete material. The following steps have been followed in our laboratory for the "Development of Geopolymer based Porous Concrete". Also, it has been presented in a flow chart for better understanding (**Refer Figure 3.2**).

- The Alkaline activator solution is prepared one day prior to casting of concrete as per mix proportion.
- Fly ash is mixed with alkaline activator solution in a pan slowly in such a way that the paste should be in the plastic state and should have sufficient consistency to provide workability to the mixture during hand mixing.
- Heating the paste in a temperature-controlled oven for 2 hours at 60ºC to complete the polymerization process.
- Sand is then mixed with the geopolymer paste 1-2 minutes before completion of polymerization.
- The heated geopolymer mortar then immediately mixed with coarse aggregate in SSD condition and cast in different moulds. Total 81 cubic specimens of size 100 mm × 100 mm × 100 mm and 27 cylindrical specimens of size 100 diameter and 200 mm length have been cast in our Civil Engineering Laboratory, Jadavpur University for testing of geopolymer based porous concrete **(Refer Table 3.3**). Smaller sized moulds have been used for testing of concrete properties mainly to reduce the wastage of materials. Cube specimens are used to test the compressive strength (at 7 days and 28 days), porosity (at 28 days) and coefficient of permeability (at 28 days). The cylindrical specimens have been used for the determination of split tensile strength (at 28 days). A detail of mixture proportions is shown in **Table 3.4.** At the time of casting of such porous mixtures in the mould, each of the specimens has been compacted by hand using 12.5 mm diameter iron rod in different layers, and each

layer is subjected to 25 blows and then vibrated for 30 sec to achieve homogeneous compaction.

- Then the molded specimens are kept in the open air in our laboratory for 48 hours and then demoulded.
- After demoulding, the entire specimens have been cured under ambient condition (27 ± 2˚C, R.H 65%) till the testing.

Table 3. 3 Total numbers of porous concrete specimen cast in laboratory

Mix no	Alkaline activating solution/fly ash ratio	FA/Aggregates ratio	Number of specimens used	
			cubical	cylindrical
GM1	0.4	1:4.0	9	3
GM2		1:4.5	9	3
GM3		1:5.0	9	3
GM4	0.39	1:4.0	9	3
GM5		1:4.5	9	3
GM6		1:5.0	9	3
GM7	0.38	1:4.0	9	3
GM8		1:4.5	9	3
GM9		1:5.0	9	3
		Total	**81**	**27**

Table 3. 4 Mix proportioning detail of geopolymer based porous concrete

Mix Specification	Alkaline activator/fly ash ratio	fly ash/ aggregates ratio	Fly ash (kg/m^3)	Coarse aggregates (kg/m^3)	NaOH soln. (kg/m^3)	Na_2SiO_3 soln. (kg/m^3)	Extra water (kg/m^3)	Sand (kg/m^3)
GM1	0.4	1:4.0	420	1680	56	98	14	117.6
GM2		1:4.5		1890				132.3
GM3		1:5.0		2100				147.0
GM4	0.39	1:4.0		1680			9.8	117.6
GM5		1:4.5		1890				132.3
GM6		1:5.0		2100				147.0
GM7	0.38	1:4.0		1680			5.6	117.6
GM8		1:4.5		1890				132.3
GM9		1:5.0		2100				147.0

Figure 3. 1 Cube and cylindrical specimens of geopolymer based porous concrete

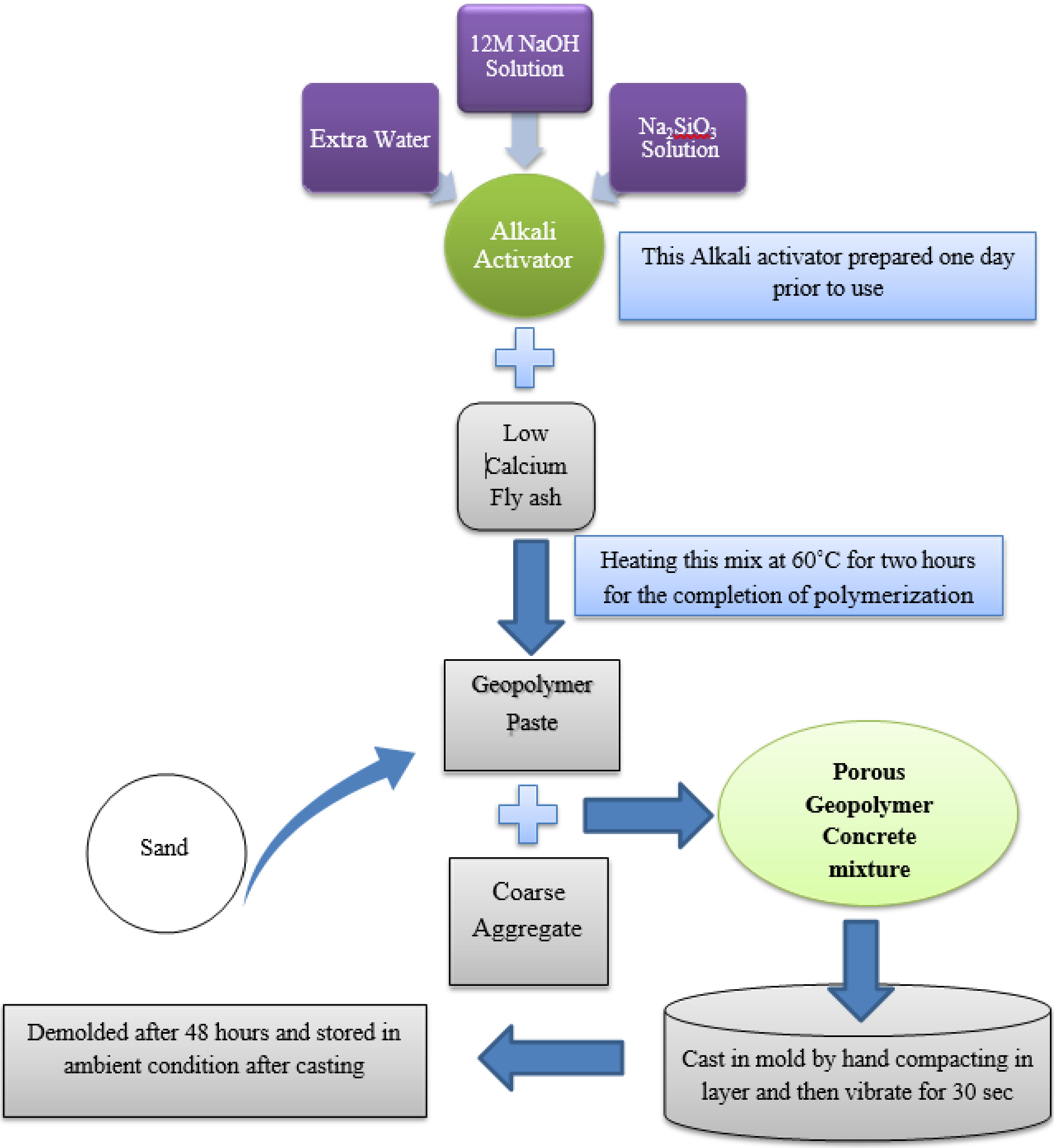


Figure 3. 2 Flow chart of the geopolymer based porous concrete mixing procedure

3.4 Testing procedures

3.4.1 Flow test: To determine the consistency or fluidity of geopolymer paste, flow table test of geopolymer binder has been done according to **IS: 1199 - 1959** (hand operator). The flow table consists of a 22 cm diameter polished steel plate. The table top is arranged for a free fall of 12.5 mm by a cam action. It also consists of one brass conical mould of 10 cm inner diameter at the base, 7 cm inner diameter at the top and 5 cm in height. The following steps are followed during the test. Top of the table and inner surface of the mould are to be cleaned. Then mould is placed in the middle of the table and filled with geopolymer paste in two equal layers. Each layer is subjected to 25 strokes with a tamping rod of diameter 12.5 mm and length 6 cm. The mould is then removed slowly by upward pulling. In this condition, the table is raised and dropped from a height of 12.5 mm, 15 times in 15 seconds. Now measure the maximum diameter of spread paste on the table. Average of two maximum diameters of spread paste has been reported as the diameter of spread.

3.4.2 Compressive strength: The Compressive strength of the porous concrete specimen has been tested using digital compressive strength testing machine. 100 mm ×100 mm ×100 mm sized cube specimens have been prepared for measuring the compressive strength. Each cube mould has been filled in three equal layers and each layer has been rodded 25 times by an iron rod of weight 2.54 kg and height of fall 30.8 cm during casting. After that, ambient temperature curing is done for the entire specimens till the testing. The Compressive strength at 7 days and 28 days are measured to understand the response with age under compression. The average of three test results is taken from three identical cube specimens and reported in this report. The rate of applied loading during the test was 5.2 kN/sec.

3.4.3 Split tensile strength: The Split tensile strength test has been performed in our civil engineering laboratory as per **IS: 516-1959**. Cylindrical specimens of size 100 mm × 100 mm in cross-section and 200 mm in height are cast and tested at 28 days. The Split Tensile strength of the specimen is calculated using the following equation.

Split tensile strength = 0.637P/ [D×L]

Where P= the maximum applied load at which failure occurs

D= Diameter of a cylindrical specimen

L= Length of the cylindrical test specimen

3.4.4 Water permeability: Constant head permeability test method has been conducted to measure the coefficient of water permeability of porous concrete. Cube specimens are tested to measure the coefficient of water permeability after 28 days of normal temperature curing. To stop the water leakage from the sides, the specimen has been covered with plaster of Paris **(Refer Figure 3.3).** During the test, the specimens are placed in between two steel plates and tightened by a screw; plumbers' putty is used at the outer periphery of the contact between steel plates, top and the bottom surface of the concrete specimen to prevent transverse water leakage through the junction. Before testing, the open surface of the specimens has been cleaned by sand paper. Under a constant water head of 500 mm, the test has been conducted, and the volume of water flow through the concrete specimen during 3 minutes at 30 seconds of time interval under a steady state of water flowing condition is noted. The test setup is shown in **Figure 3.4.**

The coefficient of permeability is calculated using Darcy's law,

$$Q = K \times i \times A / t$$

Where Q = amount of discharge over a time period **t**

K = coefficient of permeability,

A = cross-sectional area of concrete specimen

i= hydraulic gradient

Figure 3. 3 Specimens for permeability test covered with plaster of Paris

Figure 3. 4 Permeability tests set up

3.4.5 Porosity: Porosity is also an important property of the porous concrete material**.** To measure the porosity volumetrically, cube specimens have been tested after 28 days of normal temperature curing. It is calculated by measuring the volume of water displaced by the specimen when immersed in water using following equation. The average of three results has been reported and expressed in percentage.

$$P = \frac{V - Vs}{V} \times 100\%$$

Where P = porosity

V= Volume of the specimen

V_s = Volume of water displaced by the specimen when immersed in water

Chapter 4

Results and Discussion

Porous concrete is a special type of concrete unlike the traditional cement or geopolymer binding non-porous concrete materials. As we know, conventional concrete is mainly designed based on the strength requirement. But in case of porous concrete mixture design, its pore properties such as voids, porosity and water permeability are main concern rather than the strength requirement. From the previous research works conducted by many researchers it is clear that the water passing-ability through a porous concrete matrix is largely influenced by the available volume of voids and their pore connectivity. Thus, porosity and water permeability are the two key properties defining porous concrete materials. A functional porous concrete is defined as a mixture of coarse aggregates and binder material. It generally should have 15% to 25% porosity and coefficient of water permeability more than 1 mm/sec. Apart from various disadvantages of porous concrete, the low strength is the major disadvantage which decreases with the increase of porosity or voids content. Therefore, to enhance the strength property of such concrete by different techniques is the major concern. The objective of this laboratory study is to develop the compressive strength of porous concrete by maintaining suitable pore properties.

Normally, sand is not used in porous concrete. It actually minimizes the voids content and losses the pore connectivity. Therefore, its use in porous concrete mixture makes such mixture impervious. However, a small amount of sand and a blend of two typical single sizes coarse aggregate such as coarse aggregate **type I** (pass through 12.5 mm sieve and retain on 10 mm sieve) and **type II** (pass through 10 mm sieve and retain on 4.75 mm sieve) in equal proportion have been used in geopolymer based porous concrete preparation to achieve better strength property without compromising the water permeability property. Generally, cement is used in porous concrete to bind coarse aggregates together. But here in this study, an attempt has been made to develop the porous concrete using geopolymer binder. Different silica-rich materials (ex. Fly ash, metakaolin, GGBS etc.) and alkaline activator are normally used to prepare geopolymer binder. In the present study, low calcium fly ash collected from National Thermal Power Plant, Farraka and Sodium based alkaline activator solution with extra water are taken for making geopolymer binder.

A higher level of fluidity of binding material causes deposition of a thick layer of paste to the bottom of the mould during casting of the porous concrete mixture. Thus, the bottom surface of the specimen becomes impervious. So, the consistency of geopolymer paste plays an important role in case of geopolymer based porous concrete preparation. The consistency of geopolymer paste for three different alkaline activator solution to fly ash ratios of 0.4, 0.39 and 0.38 are measured by the flow table test, which is presented in **Table 4.1**. It is noted that the flow value of geopolymer paste is reduced with the reduction of the alkaline activator to fly ash ratio. However, an appreciable difference in the workability properties of porous geopolymer concrete is observed.

Table 4. 1 Flow value of geopolymer paste after 2 hours of polymerization

Mix	Alkali activator/fly ash ratio	Flow Value (mm)
GM1, GM2, GM3	0.40	120
GM4, GM5, GM6	0.39	90
GM7, GM8, GM9	0.38	75

Table 4. 2 Test results of geopolymer based porous concrete with sand

Mixture	Density (kg/m^3)	Porosity (%)	Permeability (mm/sec)	Compressive strength (MPa)		Split Tensile Strength (MPa)
				7 days	28days	
GM1	2110	15.6	1.00	15.3	18.0	1.98
GM2	2099	17.3	1.02	12.7	15.1	1.63
GM3	2082	20.0	1.06	9.70	11.4	1.23
GM4	2149	14.3	0.80	18.5	21.5	2.80
GM5	2120	17.2	1.02	13.7	16.0	1.92
GM6	2096	18.6	1.03	12.1	14.0	1.7
GM7	2229	13.8	-	21.8	24.0	3.00
GM8	2172	17.0	1.02	17.0	19.1	2.40
GM9	2160	18.5	1.03	14.6	17.0	1.80

Table 4. 3 Test results of cement based porous concrete mixtures

Mix	Cement/Aggregate ratio	Water/ Cement ratio	Density (kg/m^3)	Porosity (%)	Permeability (mm/sec)	Comp. strength (MPa)	
						7 days	28 days
M1	1:4	0.35	2091	0.17	1.07	08.33	11.55
M2		0.33	2139	0.16	1.06	10.11	12.88
M3		0.30	2130	0.14	1.02	14.11	15.11
M4	1:5	0.35	1982	0.2	1.09	07.88	09.11
M5		0.33	2023	0.18	1.06	08.77	11.33
M6		0.30	2097	0.16	1.05	11.88	12.44
M7	1:6	0.35	2002	0.22	1.14	07.00	08.00
M8		0.33	2041	0.21	1.11	08.33	10.66
M9		0.30	2068	0.17	1.07	09.66	12.00

Table 4. 4 Test results of geopolymer based porous concrete without sand

Fly ash/Aggregate	Alkaline activating soln./FA ratio	Density (kg/m^3)	Comp strength (MPa)
1:4	0.40	1988	11.11
	0.35	1899	7.77
	0.30	-	-
1:5	0.40	1970	8.88
	0.35	1751	5.54
	0.30	-	-
1:6	0.40	1837	6.66
	0.35	1842	3.32
	0.30	-	-

The test results obtained from the geopolymer based porous concrete (with sand) have been reported here in **Table 4.2**. To compare the present results, the results of cement based porous concrete have been presented in **Table 4.3**. **Table 4.4** shows the results of geopolymer based porous concrete without sand.

From the test results**,** it is noted that the density of geopolymer based porous concrete mixture (with sand) is varying within a range from 2082 kg/m^3 to 2229 kg/m^3 with an average of 2135 kg/m^3 [**Refer Table 4.2**]. Whereas, it was found 1982 kg/m^3 to 2139 kg/m^3 with an average value of 2077 kg/m^3 in case of cement based porous concrete **[Refer Table 4.3]**. Normally, the density of fly ash is less than that of cement. But, the average density of geopolymer based porous concrete mixtures has been found slightly higher than those of cement based porous concrete mixtures because of adding some fine sand into the present mixtures and it is obvious that for geopolymer based porous concrete without sand have less density [**Refer Table 4.4**].

Variation of density of geopolymer based porous concrete with the change in alkaline activator solution to fly ash ratio has been presented in **Figure 4.1**. It is noted that the density is increased with the decrease of alkaline activator solution to fly ash ratio. As expected, this is due to presence of extra water. On the other hand, the density is decreased with the increase of coarse aggregate to fly ash ratio in the total matrix. Basically, the volume of geopolymer binder is reduced as the fly ash to aggregate ratio is decreased in the total matrix, thereby reduces the density.

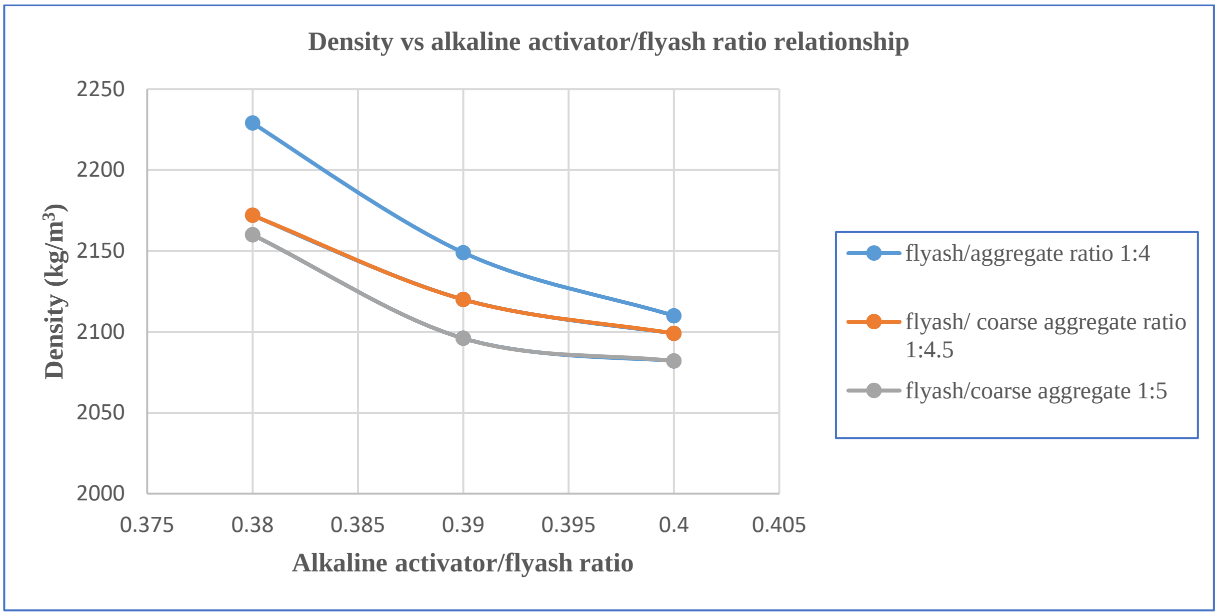


Figure 4. 1 Density vs alkaline activator/fly ash ratio relationship of the geopolymer based porous concrete mixture (with sand)

From the test results of compressive strength, to understand the effect of aging of geopolymer based porous concrete their 7 days and 28 days compressive strength have been shown in the form of bar diagram **[Refer Fig 4.2].** The compressive strength at 7 days has been found to be 80% to 92% of the 28 days compressive strength for the entire geopolymer based porous concrete mixture, whereas cement concrete can achieve only about 70% of the 28 days compressive strength **[30]**. It is notable that the early strength of geopolymer based porous concrete is more than that of cement based porous concrete mixture.

To investigate the effect of alkaline activating solution to fly ash ratio and fly ash to coarse ratio, the compressive strength (7 days and 28 days) has been plotted with the change of alkaline activator solution to fly ash ratio in **Figure 4.3 and Figure 4.4**. It is noted that the compressive strength is increasing with the decrease in alkaline activator to fly ash ratio and with the increase of fly ash to coarse aggregate ratio. It is noted that the compressive strength of porous concrete mixture is very much dependent on the thickness of paste on the surface of the coarse aggregate and proportional to each other; i.e., higher the thickness of the surface coating is leading to higher the compressive strength value. Thus, with the increase of the fly ash to coarse aggregates ratio, the total surface area that needs to be coated decreases relatively to the total volume of paste and subsequently the thickness of surface coating is increasing. Therefore, the compressive strength of geopolymer based porous concrete increases with the increase of fly ash to aggregate ratio. The other way, with the increase of alkaline activator to fly ash ratio, the amount of excess water in the mixtures is increased and it leaves more void space when the specimens are hardened. So, the compressive strength is decreased. However, a maximum compressive strength of 24 MPa and a minimum of 11.4 MPa have been achieved from such geopolymer based porous concrete mixtures, which are comparatively higher than the previous results [**Refer Table 4.4 and Table 4.5**].

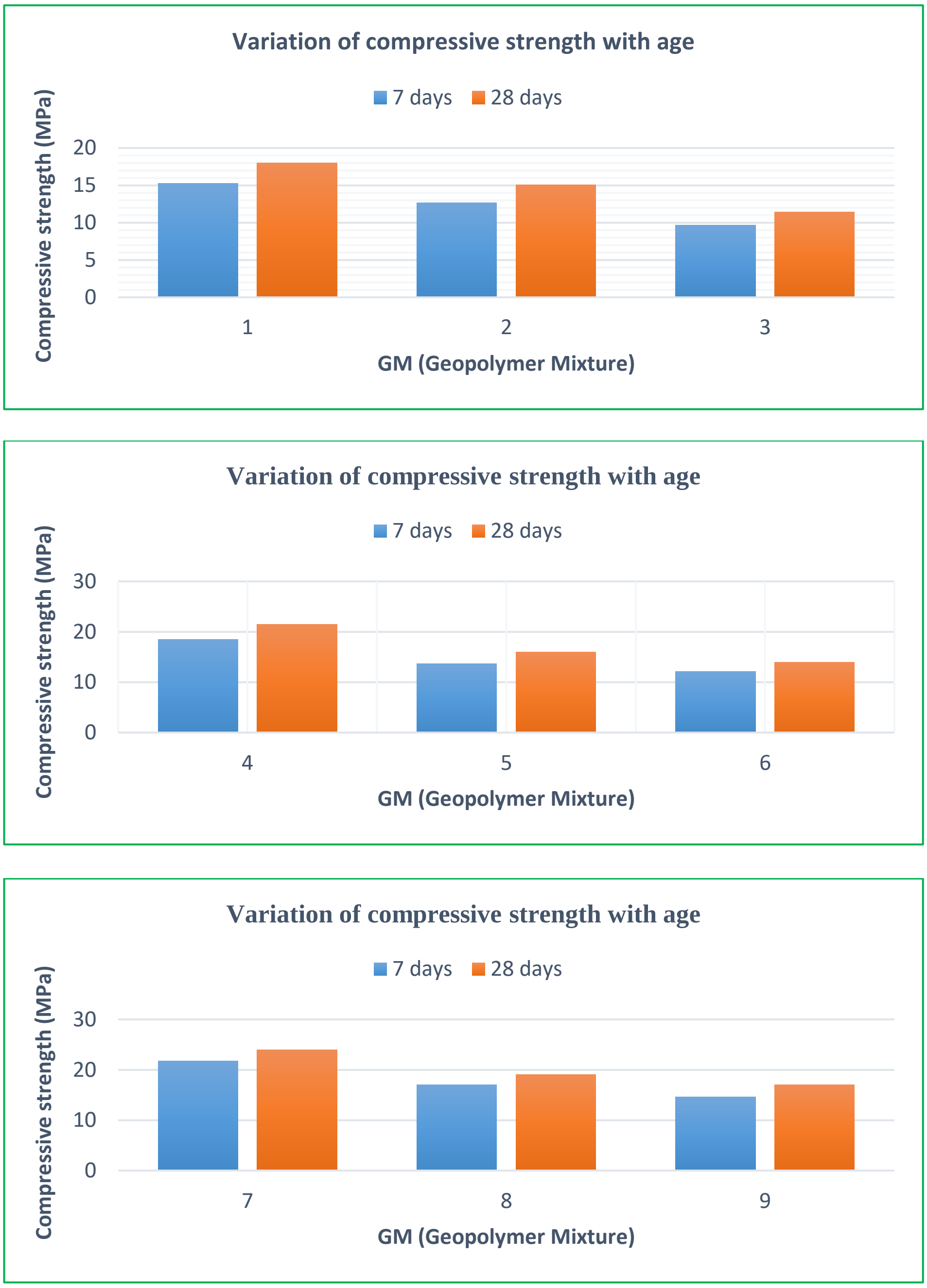


Figure 4. 2 Bar chart of 7 days and 28 days compressive strength of geopolymer based porous concrete (with sand)

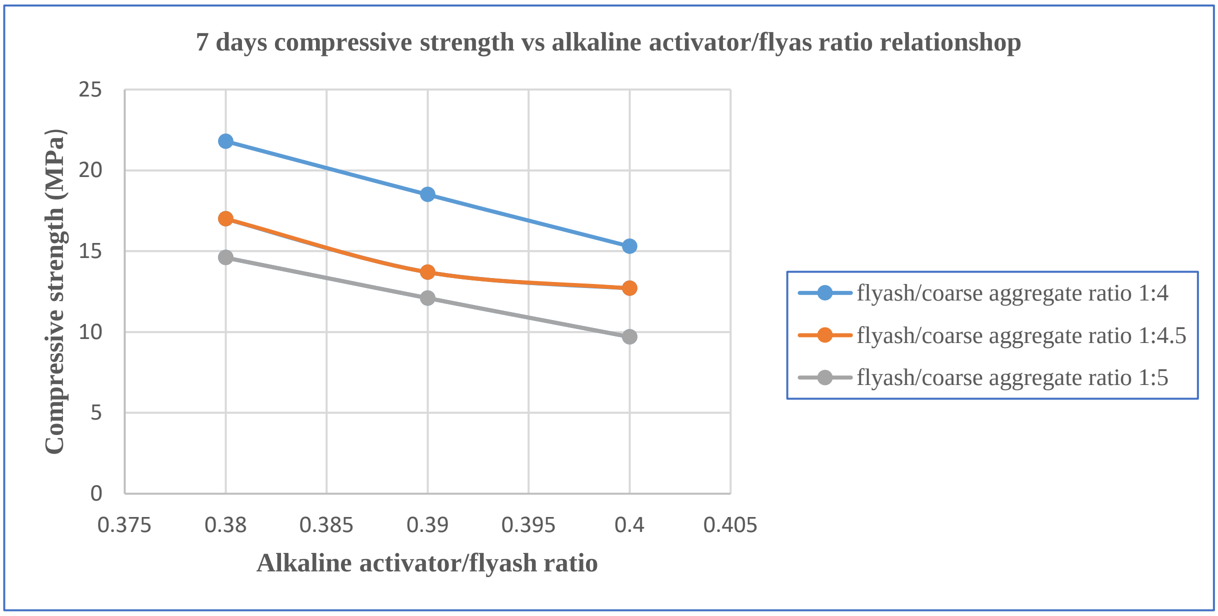


Figure 4. 3 7 days compressive strength vs alkaline activator/fly ash ratio relationship of the geopolymer based porous concrete mixture (with sand)

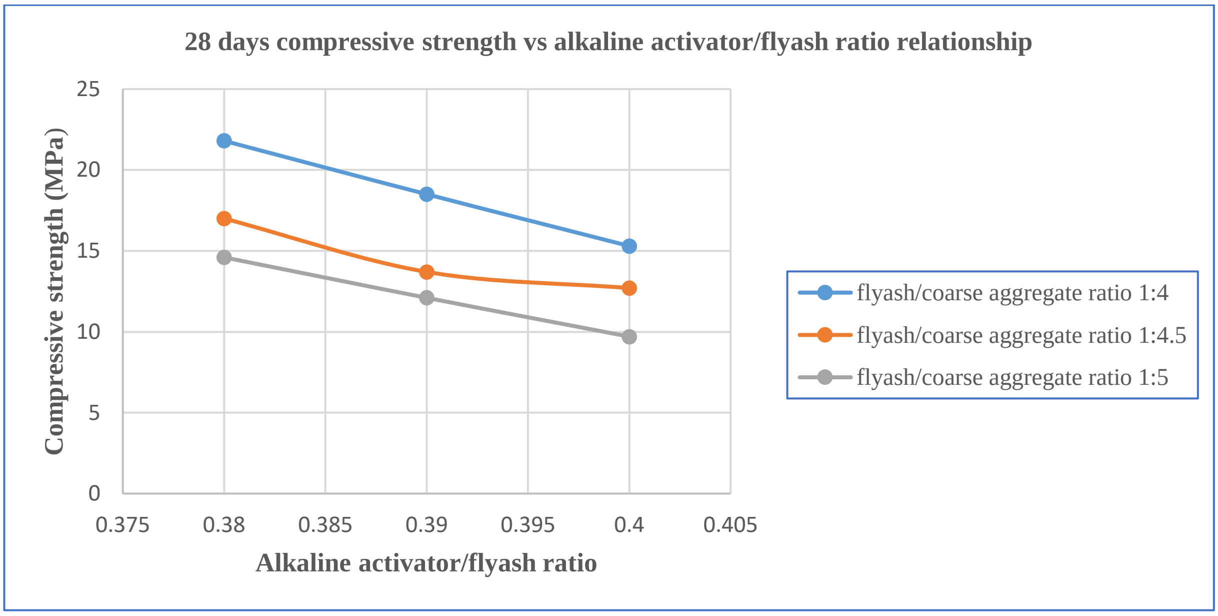


Figure 4. 4 28 days compressive strength vs alkaline activator/fly ash ratio relationship of the geopolymer based porous concrete (with sand)

The Split tensile strength of geopolymer based porous concrete at 28 days varies with alkaline activator to fly ash ratio **(Refer Figure 4.5)**. It is observed that the split tensile strength is increased with the decrease of alkaline activator to fly ash ratio and coarse aggregate to fly ash ratio. The behaviors are almost same to that of compressive strength. A maximum tensile strength of 3 MPa and minimum of 1.23 MPa have been achieved at 28 days, which is varying from 10.6% to 13% of 28 days compressive strength. However, it is noted that the split tensile strength of geopolymer based porous concrete is slightly higher than that of cement based porous concrete because geopolymer binder has better tensile strength than the cement binder **[30]**.

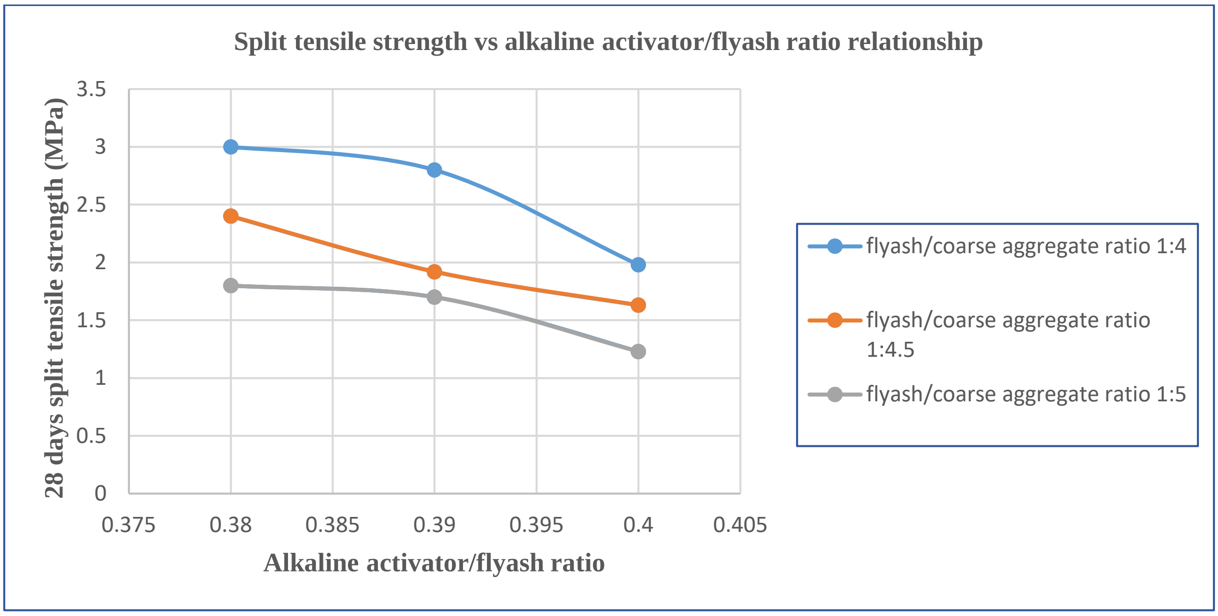


Figure 4. 5 28 days split tensile strength vs alkaline activator/fly ash ratio relationship of geopolymer based porous concrete (with sand)

Porosity is one of the main properties to characterize any porous concrete. As the minimum of 15% (recommended by National Ready Mixed Concrete Association) porosity is required to pass the water easily through porous media. But, a maximum of 25% porosity is recommended as limiting value because of low strength which is undesirable for practical applications of porous concrete. A compressive strength vs porosity relationship of the Geopolymer based Porous Concrete has been reported in **Figure 4.6**. It is clearly shown that the compressive strength is decreased as the porosity is increased **[Refer Fig 4.6],** which obviates **[30]**. It is evident that a minimum of porosity of 15% is sufficient to maintain water permeability value of 1 mm/sec. However, a maximum compressive strength of 19.1 MPa and minimum of 11.4 MPa have been achieved corresponding to their porosity value of 17% and 20%, which is relatively higher compared to the compressive strength of cement and geopolymer based no fines concrete **[Refer Table 4.4 and Table 4.5]**. This is due to the addition of some fine sand and a blend of two different single sizes coarse aggregate less than 12.5 mm.

It is further noted that for mixture **GM1** and **GM8**, the compressive strength at 28 days and their porosity values are not in order. The strength is more with higher porosity. This may be due to presence of extra water.

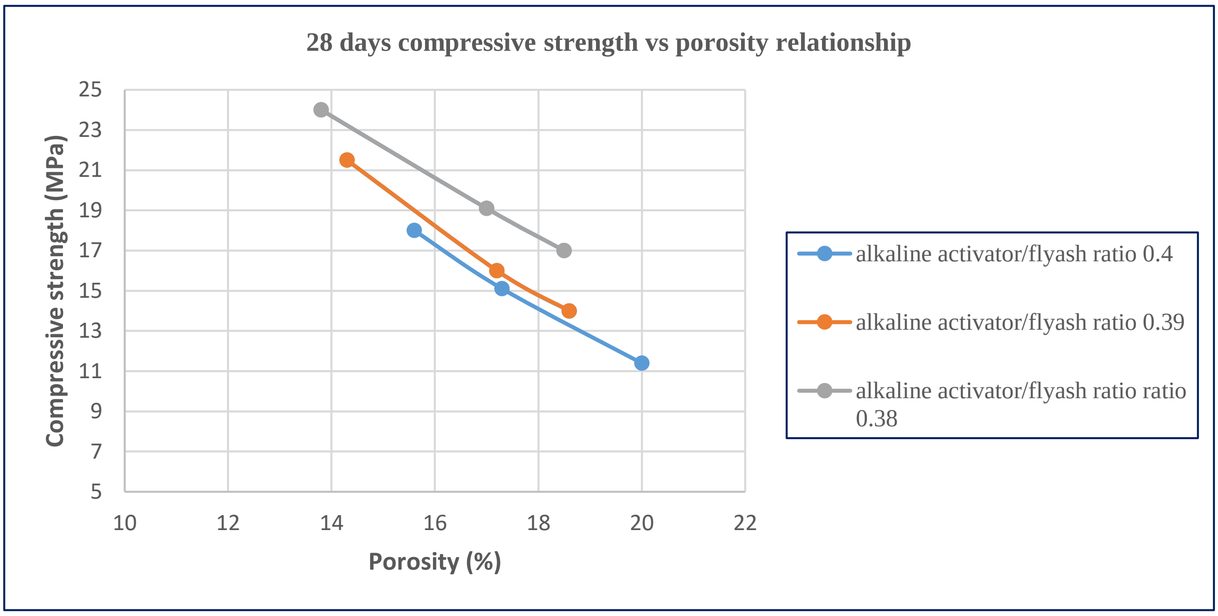


Figure 4. 6 28 days compressive strength vs porosity relationship of geopolymer based porous concrete (with sand)

A relationship between the coefficient of water permeability and porosity of the geopolymer based porous concrete mixture has been made, as shown in **Figure 4.7**. Evidently, the coefficient of water permeability is increasing with the increase of porosity **[30]**. However, a minimum water permeability coefficient of 0.8 mm/sec for the porosity of 14.3% and a maximum value of 1.06 mm/sec for the porosity of 20% have been measured. It is also noted that the present coefficient of water permeability value of geopolymer based porous concrete is slightly less corresponding to the same level of porosity of cement based porous concrete, it may happen due to the addition of small amount of sand into the present Geopolymer based Porous Concrete mixtures.

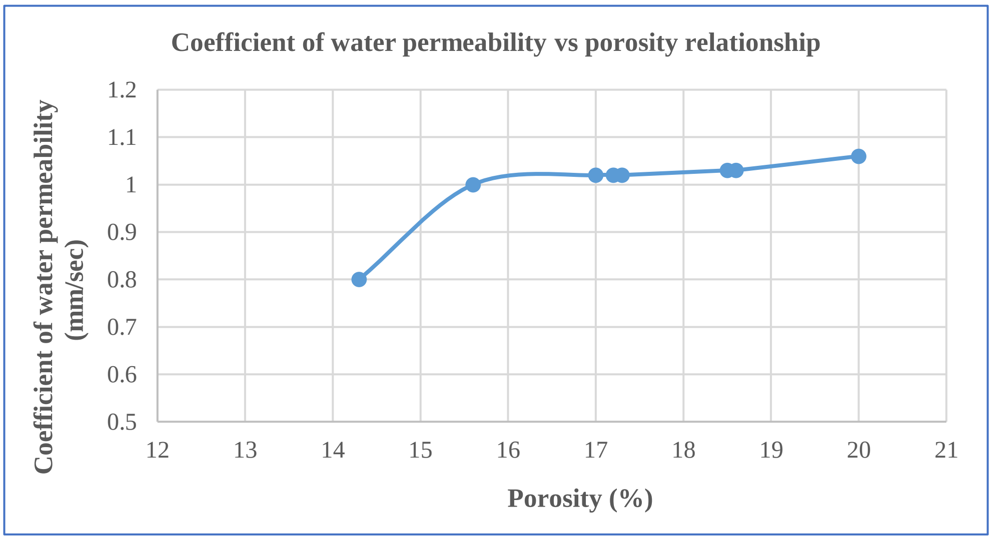


Figure 4. 7 Coefficient of water permeability vs porosity relationship of geopolymer based porous concrete (with sand)

Chapter 5

5.1 Conclusions

Based on the experimental results on geopolymer based porous concrete the following conclusions have been made:

1. The geopolymer based porous concrete having appropriate strength and water permeability can be developed.
2. The compressive strength of effective geopolymer based porous concrete (minimum water permeability 1mm/sec) varies from 11.4 MPa to 19.1 MPa at 28 days. The compressive strength of such porous concrete decreases with the decrease of the fly ash to aggregate ratio as well as alkaline activator to fly ash ratio as expected.
3. The Split tensile strength of geopolymer based porous concrete varies from 10.6% to 13% of corresponding compressive strength.
4. Density of geopolymer based porous concrete varies 2082 kg/m3 to 2229 kg/m3 for all the mixes.
5. The water permeability coefficient of geopolymer based porous concrete based on constant head permeability test method is varied from 0.8 mm/s to 1.06 mm/sec corresponding to the porosity of 13.8% and 20%.
6. It is observed that a minimum of 15% porosity in geopolymer based porous concrete is sufficient to achieve the minimum water permeability of 1mm/s.

5.2 Future scope

Following future research work is to be done before use as a pavement structure.

i. Clogging test of porous concrete should be carried out to evaluate the long-term performance of porous concrete under severe conditions.
ii. Development of porous concrete using recycled aggregate instead of natural aggregate is to be studied in detail.
iii. The thermal conductivity of such porous concrete is to be investigated.
iv. Sound absorption capacity of porous concrete are to investigate in detail.

Chapter 6

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