The Effect of Nano-silica on Concrete For Mechanical Properties

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For evaluation of Thesis ---

Dedicated

to

My Family, Faculties, and Friends

Specially Dedicated

To my mother

Late Sandhya Banerjee

Who always encouraged me to pursue my studies and is still watching me, her guiding hand will forever be on my head

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List of Contents

- Chapter 1: Introduction……...…01-04
- Chapter 2: Literature Review…….....05-44
  - Characteristics of Nano silica……...06
  - Effect of nano-silica on properties of fresh concrete…….06-07
  - Effect of nano-silica on properties of hardened concrete……...…07-28
  - Effect of nano-silica on durability parameters……28-36
  - Fracture behavior……... …. 36
  - Rate of hydration……36-37
  - Setting time…….....37
  - Workability of concrete……..37-38
  - Shrinkage and creep of concrete…….38-39
  - Microstructural images of concrete…….39-42
  - Effect of size and type of nano silica and its mixing…….....42-43
  - The combined effect of nS and mS……43-44
- Chapter 3: Statement of the Problem…….45-47
  - What are the research gaps…….....46-47
  - Objective of Research Work …….....47
- Chapter4: Materials and Methodology……..... 48-52
  - Materials used in mix design……...……49
  - Target strength of Mix Proportioning…….... 49-50
  - Selection of water-cement ratio……..50
  - Calculation of cement content……...….51
  - Proportion for Volume of course aggregate and fine aggregate content……51
  - Mix Calculation……...52
  - Mix proportion for Trial No. 1…….52
  - Characterization Technique Used …….52
- Chapter 5: Results and Discussion…….....53-68
  - XRD Analysis of Nano silica particles……...54
  - FTIR analysis of Nano silica particles……55

- Analysis of SEM Images of the Nano silica particles…….56
- Results and graphs of M25 concrete without nano silica and with nano silica……57-68

- Chapter 6: Conclusion…….....69-70
- Chapter 7: References……...71-84

List of figures

- **Fig. 1.1**. Particle size and specific surface area related to concrete materials, Sobolev etal..... 4
- **Fig. 1.2**. Morphology of nano-silica a). Nano-silica Powder, b). TEM image of nano-silica,Li et al..... 4
- **Fig.2.1**. Compressive strength of concrete with 3% nS and 0.4 w/c ratio……...10
- **Fig. 2.2**. Compressive strength of different types of concrete at different nS dosages and w/b ratios……...11
- **Fig.2.3**. Split tensile strength of concrete with 3% nS and 0.4 w/c ratio……...16
- **Fig.2.4.** Tensile strength of different types of concrete at different dosages and w/c ratios at 28days…….……...….17
- **Fig. 2.5.** Flexural strength of different types of concrete at different nS dosages and w/b ratios at 28 days……...…….…20
- **Fig. 2.6.** Elastic modulus of different types of concrete at different nS dosages at 28 days…….…….……25
- **Fig. 2.7.** Water absorption of different types of concrete at different nS dosages at 28 days…….…….……..…30
- **Fig.2.8.**Chemical shrinkageof cement paste……...…...…39
- **Fig. 2.9.** Volume shrinkage of cement paste……39
- **Fig. 2.10.** Image from backscattered electron microscopy (BSEM)……..39
- **Fig. 2.11.** Image from backscattered electron microscopy (BSEM)……40
- **Fig. 2.12.** XRD pattern of selected mortar…….…..40
- **Fig. 2.13.** XRD pattern of selected mortar…….…..40
- **Fig. 2.14.** SEM image of control mix and nano-silica with cellulose Fibers……...41
- **Fig.2.15.** SEM image of nano-silica with cellulose Fibers……..41
- **Fig. 5.1.** XRD of Silica Nano Particles……...54
- **Fig. 5.2.** FTIR for Silica Nano Particles…….….55
- **Fig. 5.3.** SEM Image of Silica Nano Particles…….56
- **Fig. 5.4.** Graph of compressive strength without nano-silica concerning days……...57
- **Fig. 5.5.** Graph of compressive strength with nano-silica (1.5%) concerning days…58
- **Fig. 5.6.** Graph of compressive strength with nano-silica (3%) concerning days…...59
- **Fig. 5.7**. Graph of compressive strength with nano-silica (4.5%) concerning days…60
- **Fig. 5.8.** Graph of compressive strength with nano-silica (6%) concerning days…...61
- **Fig. 5.9.** Graph of compressive strength of all percentages for 7 days……63
- **Fig. 5.10.** Graph of compressive strength of all percentages for 14 days……63
- **Fig. 5.11**. Graph of compressive strength of all percentages for 28 days……64
- **Fig. 5.12**. Graph of compressive strength with nano-silica (6%) with extra water concerning days……65
- **Fig. 5.13.** Graph of compressive strength with 6% nano-silica mixed concrete with constant water and extra water concerning days……..66
- **Fig. 5.14.** FESEM Image of concrete without Nano silica particles……67
- **Fig. 5.15.** FESEM Image of concrete with Nano silica particles……67

List of Tables

- **Table2.1: -**The effect of 3% nS on concrete compressive strength at 0.4 w/c ratio.....11-12
- **Table2.2.: -**The effect of nS on the compressive strength of different types of concrete……...12-15
- **Table2.3: -**The effect of nS on the tensile strength of different types of concrete……...17-19
- **Table 2.4: -**The effect of nS on flexural strength of different types of concrete…21-23
- **Table2.5: -**The effect of nS on the elastic modulus of different types of concrete……...25-27
- **Table2.6: -**The effect of nS on water absorption in different types of concrete...31-33
- **Table 5.1: -**Mix design of concrete without nano-silica……..57
- **Table5.2: -**Mix design of concrete with nano-silica of 1.5%(90gm) …….58
- **Table5.3: -**Mix design of concrete with nano-silica of 3%(180gm)……...59
- **Table5.4: -**Mix design of concrete with nano-silica of 4.5%(270gm)……60
- **Table5.5:-**Mix design of concrete with nano-silica of 6%(360gm)……61
- **Table5.6: -**Comparison of compressive strength of all percentages according to days……...62
- **Table5.7: -**Mix design of concrete with nano-silica of 6%(360gm) with extra water…….65
- **Table5.8:-**Comparisons the 6% nano silica mixed concrete with constant water and extra water……66

Chapter 1
Introduction

1. Introduction: -

Concrete is considered one of the most commonly used materials in the world, with an estimated annual production of 27.3 billion tonnes in 2015, making an average of about 1.6 m3 for each person on the earth [1]. Portland cement, the essential concrete binder, accounts for nearly 80% of total concrete CO_2, emissions, sharing 5 to 7% of total CO2, emissions on this earth [2–7]. The demand for Portland cement will likely increase by nearly 200% over 2010 rates by 2050, reaching 6,000 million tonnes a year[8]. Therefore, the key sustainability challenges for the next decades are developing and manufacturing concrete with fewer clinkers and causing lower carbon dioxide emissions than the traditional ones, while offering the same reliability and much better durability [9]. Peris Mora [10] has described the significance of durability in building materials for eco-efficiency, stating that an increase in concrete durability from 50 years to 500 years could scale down the impact on the environment by a factor of up to 10. Pacheco et al. [8] reported that increasing the concrete compressive strength could reduce as much as 50% in the use of reinforced steel. Durable and high-strength concrete is the main concern in its future production as far as material and eco-efficiencies are concerned [11]. The application of the nanoparticles to enhance the durability and mechanical properties of the cementitious composites was explored in the report of RILEM Technical Committee 197- Nanotechnology in Construction Materials (TC 197-NCM) [12]. The use of nanoscience and nanotechnology in cementitious composites was reported in late 1980 and became active for almost two decades [13]. Nanomaterials have excellent properties and functions that can provide cementitious composites high performance with high mechanical and durability properties and multifunctionality and intelligence [14–18]. Nano-metallic and nonmetallic oxide cementitious composites were first used to modify or enhance the properties of the cementitious materials [19]. By recognizing the structure at its nanolevel, a new generation of high-performance building materials can be updated, synthesized, and engineered. With the advancement in technology, the structure of the composites at the atomic level can be observed, and their various properties of different phases can be evaluated at a nano level [20]. The concept of packing of particles at the nanoscale can, therefore, be used to improve the performance of the composites. This very thought led the researchers to nano-silica (nS) particles and nano-fibers to enhance the strength, durability, and processing characteristics of cement composites [20]. Novel properties of nanoparticles of sizes 1–100 nm have drawn immense interest over the past decades [21]. One of the main features of the nanoparticles is their high volume to the surface area, Fig. 1 [22]. Several nano-sized particles are used as nano-additives in cement-based materials to enhance their properties at the macroscopic level and improve their functionality, and silica nanoparticles or nano-silica have become common among those nano-sized particles [23]. Nano-silica (nS) or silica nanoparticles, also known as silicon dioxide nanoparticles, can be used as additives for improving concrete's mechanical and durability properties [24–26]. The effect of nS on the nanostructure of cement paste also confirmed the improvement in concrete durability [27]. The results revealed the nS as an excellent alternative to reduce consumption of cement in the production of high-strength concrete (HSC) [28]. Using nS as a cement replacement makes concrete more cost-effective and reduces the CO_2 footprint of the concrete products [29]. Due to their improved performance in filling effect and particle size distribution, thereby decreasing the

porosity in concrete and increasing their pozzolanic reaction with calcium hydroxide (Ca (OH)2 or CH) to yield CSH, nS has gained particular attention in comparison with conventional minerals admixtures [30,31]. Such behaviors of nS resulted in improved mechanical properties in the concrete mix [32–34]. The cement setting process was enhanced by nS compared to silica fumes (SF) [35] and decreased bleeding and segregation and increased cohesiveness of fresh mixes [36]. Nano-silica facilitates the hydration of cement at a very early age, and it can consume and convert calcium hydroxide into CSH gel due to its high pozzolanic action, thus enhancing the concrete's mechanical properties [37]. The morphology of nS in powdered form and under a transmission electron microscope (TEM) is shown in Fig. 2 [38]. R. Olar, in 2011, reported a reduction in the use of nanomaterials in construction due to lacking knowledge of suitable nanomaterials and their behavior, a lack of specific design standards for constructing elements using nanomaterials, a lack of detailed information on the contents of nano products, its high costs and unknown health risks involved in handling nanoparticles [39]. However, a considerable rise in the number of publications in the area of nanotechnology-based eco-efficient construction materials has been noticed over recent years [23]. Extensive research on choice of the nanomaterials, such as silicon dioxide nanoparticles (Nano-SiO_2 or nano-silica), titanium dioxide nanoparticles (TiO_2), carbon nanotubes, nanoparticles of zinc oxide (ZnO), silver (Ag), aluminum oxide (Al_2O_3), and zirconium oxide (ZrO_2), etc., their effects on concrete, and building elements at different loading conditions and circumstances must be carried out to encourage the wide-scale application of nanomaterials in the construction field [25,39]. Different materials being developed for construction industries will revolutionize not only.

Although cement concrete poses the greatest environmental threat to the globe, it is nonetheless widely utilized as a building material for many different types of construction. Engineers are unable to create a suitable material from waste or in another way to replace cement concrete. Regretfully, engineers have been attempting to enhance cement concrete's performance through the use of pozzolanic elements rather than creating a substitute. Throughout the past fifteen years, research has been conducted on the application of nanomaterials, such as nano-SiO_2, in cement concrete. It performs a vital role as an activator by devouring the calcium hydroxide. It enhances pozzolanic activities in the presence of water and unburned calcium hydroxide to improve the strength and durability of concrete.

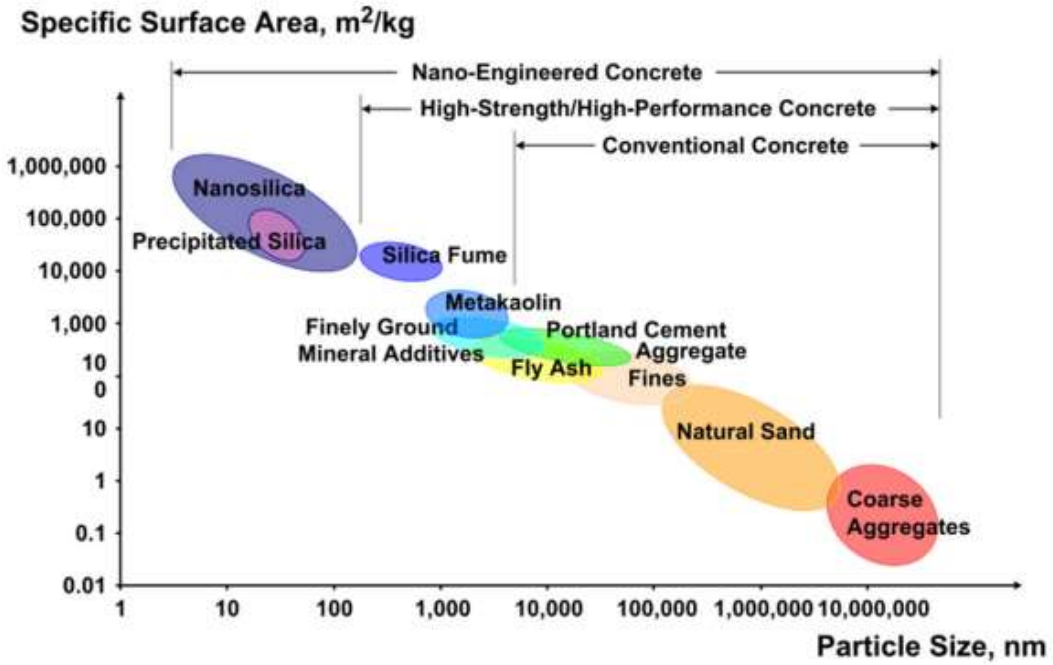


Fig.1.1. Particle size and specific surface area related to concrete materials, Sobolev et al. [22].

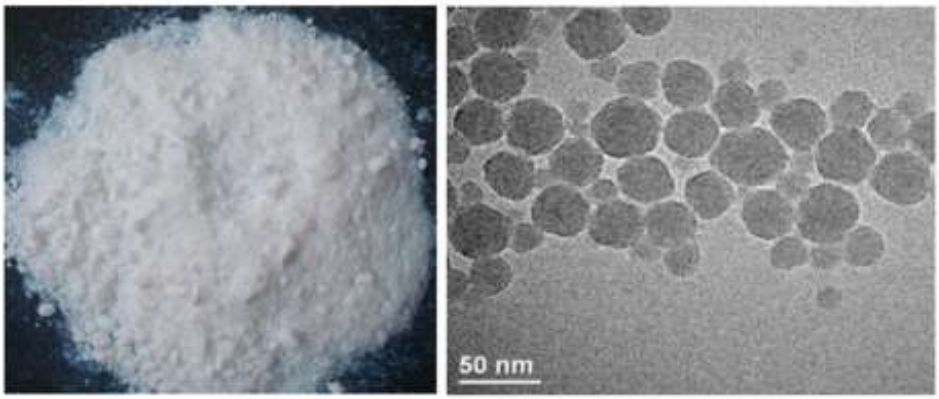


Fig. 1.2. Morphology of nano-silica a). Nano-silica Powder, b). TEM image of nano-silica, Li et al. [38].

Chapter 2
Literature review

2. Literature Review: -

2.1. Characteristics of Nano silica (nS): -

Nano-silica is a white soft and fluffy powder containing SiO_2. Its strong surface absorption is a result of its particle size's nano order. Because of its huge surface area, greater chemical purity, and noticeable amorphous dispersion, nano-silica is an important pozzolanic activator. It is categorized as different particle sizes of hydrophilic and hydrophobic nano-silica. Because hydrophilic nanosilica disperses well in water, it is employed in cement concrete.

2.2. Effect of nano-silica on properties of fresh concrete: -

The interaction of nS particles in fresh concrete shows their influence on different properties of fresh concrete, such as workability, setting time, consistency, etc. Zhang et al. [34,41] reported that the use of 2% nS particles in high-volume fly ash (HVFA) and slag concrete reduced initial as well as final setting times. Ghafari et al. [42] and Jalal et al. [43] also noticed a similar effect of nS on setting times in ultra-high-performance concrete (UHPC) and high-performance self-compacting concrete (HPSCC), respectively [45]. Different researchers reported a decrease in workability in nS-incorporated concrete [37,42,44]. Ghafari et al. [42] reported an increase in demand for water as the percentage of nS in concrete increased, which is attributed to the fineness or high specific surface area of nS particles and the immediate interaction between nS and liquid face cementitious mix [37] and the high-water absorption level of nS [44]. Mukherjee et al. [45] found that the slump value decreased as the amount of nS increased in the concrete. Due to the high surface area of the nS particles and the unsaturated bonds in nS, a portion of the mixing water (water molecules) attracts towards the surface of nS particles and thus produces silanol (Si-OH) groups. As a consequence, the water needed for the fluidity of the concrete mixture becomes insufficient, according to [45]. Ghafari et al. [42] observed that for an acceptable range of slump flow, the highest amount of nS that could be added is 3% by weight, and the same was also confirmed by [44]. However, the research conducted by Jalal et al. [43] on HPSCC showed that concrete workability was not much affected by the addition of 2% nS. Well-dispersed and de-agglomerated nS led to a substantial increase of about 35% in concrete workability, which can be due to the presence of free water among the ultra-fine particles that facilitates the rolling effects between the particles [46]. It indicates that a better dispersion of nanoparticles can even improve concrete workability. The studies on recycled aggregate concrete (RAC) containing nS found that the water absorbed by the recycled aggregate (RA) and nS particles resulted in the loss of slump, and the greater was the loss at the higher nS dosage [47]. Elrahman et al. [48] reported that incorporating nS decreased consistency and thus increased the viscosity of the fresh mixture. The content of the air in nS-incorporated concrete mixes was high compared with the reference mix due to the high viscosity of the paste with nanoparticles of the high specific surface area [49]. In self-compacting lightweight aggregate concrete (SCLC),

replacing cement with nS reduced the fresh density and increased its consistency [50]. Cho et al. [51] reported that the rheological behavior of lightweight foam concrete (LWFC) improved by adding a small number of nS particles as the stress growth rheometer test showed a significant increase in static and dynamic yield stresses.

2.3. Effect of nano-silica on properties of hardened concrete: -

(I) Compressive strength: -

According to studies [34,41,42,48,52–57], even a small dose of nS in concrete at an early age can significantly enhance compressive strength. The maximum early and 28 days compressive strength observed at 2 to 3% replacement of nS indicates that the optimum dose of nS lies within this range [34,37,41– 43,53,54,58,59]. Nano-silica with small particle sizes exhibited a higher early-age strength in comparison to bigger particles [41]. NajiGivi et al. [60] reported that nS with 15 nm average particle size increased concrete strength at the early ages as compared to 80 nm particles, but the 90-day compressive strength was higher in concrete with 80 nm nS particles. Belkowitz et al. [61] observed that cement composite with larger nS particles exhibited higher levels of enhancement in compressive strength and elastic modulus by more than 20% of the reference mixtures. Belkowitz's study also recorded a 20% increase in compressive strength at the lowest doses of the smallest (5 nm) nS particles and a 14% reduction in compressive strength at their highest doses, compared to the reference concrete. This reduction of strength at high nS dosage is attributed to more agglomerated sites and voids produced by the high content of small nS particles in concrete. According to Elkady et al. [46] the agglomeration of the nS particle could result in loss or gain of compressive strength depending upon the degree of agglomeration. Li et al. [62] reported that the difficulty in achieving uniform dispersion of nS (10 ± 5 nm size) in concrete at their higher dosage caused the formation of weak zones in concrete as the study showed a higher compressive strength for 1% nS compared to 3% nS concrete. It may be hypothesized that small nS particle agglomeration could have created the weak zones. Li et al. also observed poor workability at a higher dose of nS, which led to the development of microcracks in concrete. However, the investigation by Saloma et al. [63] on nanomaterial concrete reported that the compressive strength increased as the nS content increased up to 10%. Elkady et al. [64] reported a 13.5% gain in compressive strength at 4.5% nS dosage in nS concrete at 7 days while 1.5 and 3% Ns resulted in 3 and 4.5% strength gain compared with the control specimen. However, at 28 days, the gain in strength was 43.5% at 3% and 17.5 and 29% respectively at 1.5 and 4.5% nS dosages. According to the study, the agglomeration of the nS particles caused a long time for its reaction with excess CH to form CSH gel, and the agglomerated nS particles acted as filler materials, which reduced porosity, causing the improvement of early age strength. The optimal 3% dose of nS also improved the bond strength by 38.5% compared to the control sample as reported by [64]. Singh et al. [24] reported that the nS particle yielded a higher early-age compressive strength in nano-engineered FA concrete. It was observed that the nS particles are highly effective in improving compressive

strength in UHPC at 3 days compared to 7 and 26 days implying that the nS particles considerably promote the hydration process of cement at early ages [9]. The studies [25,26] suggest that the nS particles accelerate the early hydration rate and modify the CSH packing density from low to high. Chithra et al. [65] reported higher production of CHS in high-performance slag concrete (HPSC) with 2% nS at early ages with a very compact structure. The high-density CSH is responsible for the high early strength and at a later age, the hydration process is impeded by the reduced porosity of the concrete in the presence of nS particles [66]. According to a recent study in nS concrete [45], the increase in early-age compressive strength is due to the high pozzolanic activity of nS at an early age. Whereas the increase in 28 days compressive strength is due to the filling up of voids by the CSH gel formed and strengthened mortar-aggregated bonding. The smaller and finer nS particles filled the space between the grains in the cement paste and caused the development of the strength, according to [67]. Dolomite concrete containing 2% nS exhibited a higher compressive strength; however, the strength was reduced at 4% nS [68]. Fallah et al. [69] reported that the compressive strength increased by 14 and 8.6%, respectively, in the HSC with macro-polymeric and polypropylene fibers, at 2 and 3% nS. The result also showed that 3% nS with 0.2% polypropylene (PP) contributed a 13.5% increase in strength compared to the plain concrete. Because of the increased formation of hydration products in the presence of nS particles, the mechanical properties of GGBFS admixed self-compacting concrete (SCC) increased by adding up to 3% nS particles [70]. The study also found that nS particles above 3% resulted in a lowered strength due to the reduction in crystalline CH content needed for CSH gel formation. In a study by Heidari et al. [71], it was observed that adding 0.5 to 1% nS to ground ceramic powder concrete improved the negative effects of ground ceramic powder on the mechanical properties of concrete. The high reactivity of nS with the CH produced during the process of hydration resulted in an increase of compressive and tensile strengths of the HPSCC at the early ages and a large amount of reaction products formed due to the subsequent hydration acceleration [43]. According to Puentes et al. [72], the high evaporation rate in SCC with smaller nS particles induced large open porosity at 7 days; however, at 28 days, the high pozzolanic activity increased the strength of SCC. Hameed et al. [73] reported an increase in SCC compressive strength with increased colloidal nS (CnS) content and found that the compressive strength increased from 29.32% to 48.1%, compared to the reference concrete, as the CnS increased from 2.5% to 10%, respectively at 28 days. A steady increase in compressive strength was also reported by Massana et al. [74] with the addition of nS up to 7.5% in HPSCC, but the increase was only around 13% at 28 days compared to the reference mix. However, relative to the reference mix, this study reported the highest increase in compressive strength of 31% when 2.5% of nS and mS used in combination. This is attributed to, according to de Abreu et al. [28] a synergy effect or a combined effect of both nS and mS in the concrete, which is of chemical in nature in addition to the physical effect which led the concrete particles to be better packed. At all the stages of the test from 3 to 91 days, the SCC showed the highest compressive strength for colloidal nS (CnS) compared to its powdered form, and at the same time, the reference and powdered nS concrete specimens displayed the same compressive strength at 7 and 28 days [49]. However, according to the above investigation, the first-day strength of the reference concrete was more than that of nS concrete. Puentes et al. 2015 [72] reported a lower strength in nS-incorporated SCC at 1 day but a higher strength at 28 days. The

addition of nS solution to the concrete mix in comparison with an equivalent amount of powdered nS moderately improved the concrete strength after 28 days but not the early strength [75]. Alhawat et al. [55] reported that the ultra-high surface area of nS increased the acceleration of the hydration process. The large quantity of hydration products made the concrete denser and more homogeneous [42] than ordinary concrete as the voids in the micro cement particles were filled by the nanoparticles of the silica [76]. Du et al. [77] reported that due to the high hydration rate in the presence of nS particles, the early age strength of the lightweight concrete (LWC) was improved; however, such gain in strength was diminished with prolonged curing time. The self-compacting lightweight aggregate concrete (SCLC) showed a higher 28-day compressive strength at 0.25, 0.37, and 0.5 water binder (w/b) ratio for the replacement level of nS up to 5% [50]. Adding 3% nS to high-strength lightweight concrete (HSLWC) minimized the negative effect of the coarse lightweight aggregate and contributed to a significant improvement in the mechanical properties of the concrete [67]. Elrahman et al. [48] noted an increase in compressive strength in LWC with nS up to 4%. NajiGivi et al. [78] and Nazari et al. [79] observed that cement could be replaced advantageously with 2% nS of 15 nm average particle size while the samples cured in the solution of lime for 28 days, however, for the water cured samples the optimum amount of nS was only 1%. It may be ascribed to the excessive nanoparticles (pozzolans) that are required, in water curing, to react with lime liberated during the process of hydration, thus causing the leaching of excessive silica and subsequent strength deficiency as it replaces a portion of the cementitious material and not contributing to the further improvement in the strength [80]. While lime curing, a large amount of CSH gel was formed as the amount of nS (pozzolan) present in the concrete mixture was close enough to react with lime liberated during the process of hydration and causing less silica to leach out compared to the water cured samples [78]. The rapid development of the compressive strength of nS concrete showed that nS acts as a filler to increase the concrete density and an activating agent for hydration reaction [81]. Experimental results [75] of plain concrete indicated that incorporating just 0.1% nS into it increased the strength by 84%, 93%, and 35% at 3, 7, and 28 days, respectively, for the water-cement ratios (w/c) between 0.42 and 0.45. The concrete with 0.65 w/b ratio yielded a substantial increase of 41% in 28 days of compressive strength at 1.5% nS, while the gain was only 6.5 and 0%, respectively, at 0.55 and 0.5 w/b ratios [82]. Makarova et al. [75] reported that the increase in nS content from 0.05% to 0.5% considerably improved the strength of the concrete but, a further increase of nS to 1% did not affect the strength. According to Du et al. [52], the decrease in porosity and refined pore structure due to the pozzolanic reaction at a small dose of 0.3% nS in concrete increased the early age compressive strength. Application of nS increased both the short and long-term strength of HVFA concrete [83] as concrete with 50% FA and 4% nS showed an 81% rise in strength in one day, 9.5% in one year, and 6.8% in two years. The inclusion of nS in HVFA concrete enhanced both the early age and 28 days compressive strengths [54] and is comparable to the results obtained by [34]. At 28 days, the addition of 3 and 6% nS to concrete with 30% fly ash (FA) exhibited compressive strength equal to or greater than that of non-fly ash concrete [84]. The nS concrete achieved the characteristic compressive strength in half of the time required by the reference concrete and concrete with micro-silica (mS) to achieve the same strength [56]. Concrete samples with 1% nS and with 1% nS plus 25% FA showed the same compressive strengths at the 29th and 87th day

tests [76]. Results also showed that nS addition improved the long-term strength development in HVFA concrete with 40% FA [54]. Researchers have compared the effect of nS and silica fume (SF) or mS on the properties of different types of concrete. Hasan-Nattaj et al. [44] reported that SF exhibited better performance than nSin improving the compressive strength in steel-fiber concrete. Singh et al. [24] reported a 40% strength gain within 28 to 90 days for concrete with 30% FA and with 30% FA plus 6% SF, on the other hand, in concrete with 30% FA plus 3% nS mix, the gain in strength was reduced to 19%. As stated earlier, this may be due to the increased hydration rate at the early stage and modification low-density structure of CSH to its high-density structure in the presence of nS [25,26]. However, according to Bastami et al. [85], the addition of nS in HSC was more effective than the addition of SF to enhance the residual compressive strength of the heated specimens. In UHPC, with increased nS content up to 1%, the flexural to compressive strength ratio increased, and the nS content of more than 1% contributed to a decrease in this ratio [38]. The study also observed that cement replacement with optimal content of 1% nS and 3% nano-limestone (nC) in UHPC increased the mechanical strength and formed a dense microstructure. In the case of recycled aggregate concrete (RAC), due to improved concrete quality, a consistent improvement in compressive strength was also noticed at 7, 24, and 90 days, with an addition of 3% nS, according to Mukherjee et al. [47]. Erdem et al. [86] reported an improvement of compressive strength in RAC even at a small dose of 0.5, 1, and 1.5% due to a quickened hydration process and pozzolanic reaction, which resulted in forming a strong bond between mortar and aggregates. The application of silica nanoparticles at a small amount of 0.4, 0.8, and 1.2% resulted in a compressive strength increase of 10, 18 and 22% for mixtures containing 50% recycled aggregate (RA) and 6, 13 and 16% for mixtures with 100% RA, respectively [87]. Fig. 3 gives a comparison of the compressive strength of concrete with 3% nS at 0.4 w/c and Fig. 4 gives the effect of nS on compressive strength in different concretes with its different dosages at different ages. The details of the studies are given in Tables 1 and 2.

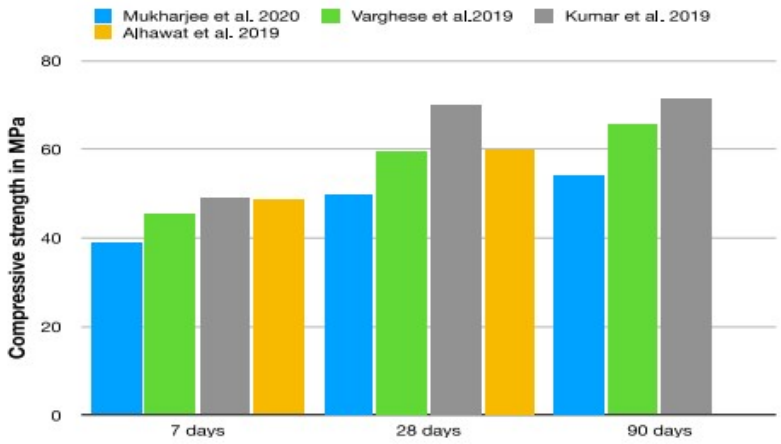


Fig. 2.1. Compressive strength of concrete with 3% nS and 0.4 w/c ratio.

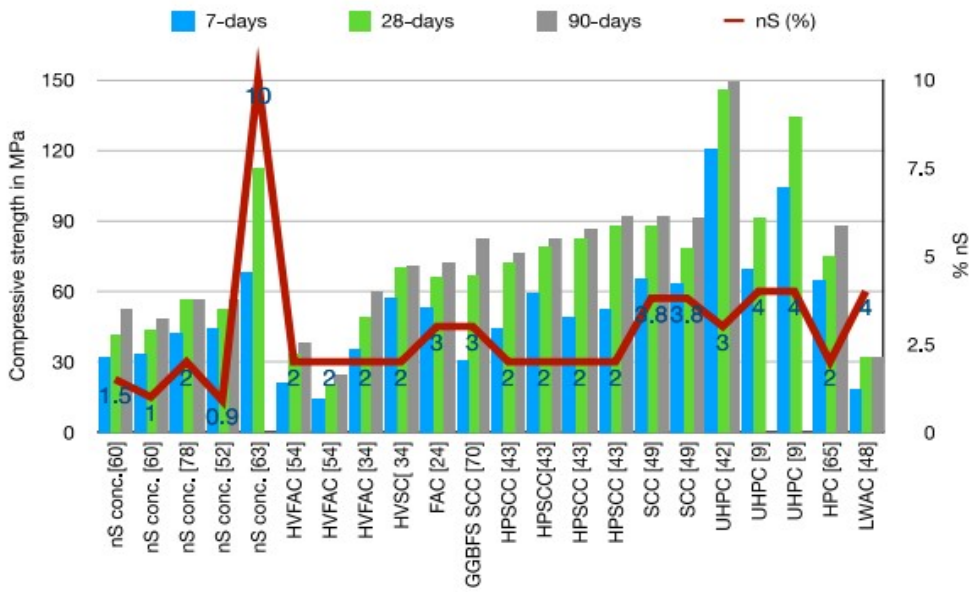


Fig. 2.2. Compressive strength of different types of concrete at different nS dosages and w/b ratios.

Table 2.1: -

The effect of 3% nS on concrete compressive strength at 0.4 w/c ratio.

Author	Type of nS	Size/Suface area of nS	Remarks
Mukharjee et. al.,2020[45]	Colloidal	8–20 nm	In the concrete with 3% nS at 28 days, the compressive strength increased by 20%, compared to the reference concrete. The same trend was observed at 90 and 365 days of compressive strength test.
Varghese et. al.,2019[56]	Colloidal	8–20 nm	The compressive strength of high-performance concrete with 3% nS gained 33.25% of the selected characteristic compressive strength of 40 MPa (fck) just in 24 h. At 7 days, the strength exceeded by 13.5% of 40 MPa.
Kumar et. al., 2019[37]	Powder	22000m^2/kg	The concrete added with 3% nS as a replacement for cement showed higher compressive strength and improved

			durability properties. Compared to the reference concrete, the compressive strength of 3% nS increased by 31.42%.
Alhawat et. al.,2019[55]	Colloidal	15nm	The concrete compressive strength is directly affected by the specific surface area of nS particles. A greater increase in compressive strength is observed at 3% nS of 250 m2/g specific surface area (SSA) compared with nS of 51.4 m2/g and 500 m2/g SSA. 51.4 m2/g nS particles is observed as least effective in strength improvement. The w/b ratio also influences the improvement of the strength of nS concrete. The optimum amount of nS replacement was closely associated with the nS particles' reactivity and agglomeration level.

Table 2.2.: -

The effect of nS on the compressive strength of different types of concrete.

Author	Type of concrete	Type and sizes of nS	Remarks
Najigivi et al., 2010[60]-I	Concrete with nS	Powder 15nm	The compressive strength increased for replacement up to 1.5% for 80nm particles and up to 1% for 15 nm particles. However, at 2%nS, the strength was still higher than the reference mix.
Najigivi et al., 2010[60]-II	Concrete with nS	Powder 0nm	The compressive strength of concrete with 80nm nS declined up to 28 days compared to the concrete with 15nm; however,80nm nS concrete showed a higher value of compressive strength at 90 days. w/b=0.4
Du et al.,2014 [52]	Concrete with nS	Powder 13nm	The concrete specimens with 0.3 and 0.9% nS were tested

			for compressive strength. The strength increased due to the nano-filler effect and pozzolanic activity with an increase in nS content. Even at small dosages of 0.3 and 0.9% nS, the 28 days compressive strength increased by 9 and 12%, respectively, relative to the reference concrete. w/c=0.49.
Saloma et al. 2013[63],	Concrete with nS	Powder 10–140nm	As the nS content increased upto10%, the compressive strength also increased. The compressive strength of Ns concrete increased in the range between 3.82% and 11.84% at the age of 3 days, but the strength increase ranged from 3.87% to 17.24% and 4.93% to 24.59% at the age of 7 and 28days, respectively. This shows that for up to 3 days, the hydration reactions take place only between cement and water. After 3 days, nS reacts with free calcium oxide and forms a new cement paste. This indicates that the nS particles influence to increase the compressive strength after 3 days.w/c=0.2
Shaikh et al., 2014[54]-I	HVFA(38%FA)	Powder 25nm	By adding 2% nS, the compressive strength of HVFA (38%FA+2%nS) is increased approximately by 20,23, 14%at7,28, and 90 days respectively. The water-to-cement ratio used is 0.4.
Shaikh et al., 2014[54]-II	HVFA(58%FA)	Powder 25nm	The compressive strengths of HVFA with 60% FA and HVFA with 58% FA+2% nS are almost the same for up to 90 days. The strengths observed for these samples are less compared to the HVFA with 38%FA + 2%nS. w/c=0.4

Zhang et al., 2012[34]-I	HVFA(48%FA)	Powder 12nm	2% NS, 48% fly ash, 50 %cement at 0.45 w/c. The strength increased by 25,13,18% for7,28, and 91 days respectively, compared to the reference mix of 50% cement and 50 %FA.
Zhang et al., 2012[34]-II	High Volume slag	Powder 12nm	2%NS, 48%slag,50%cementat0.45w/c. The strength increased by 18,3and3%for7,28and91days respectively compared to the reference mix of 50% cement and 50%slag. The strength increased by 18,3and3%for7,28, and 91 days, respectively, compared to the reference mix of 50%cement and 50%slag. The strength of the ITZ is increased significantly by the low w/c in the presence of nS, resulting in the high compressive strength. However, the strength is increased to such aggregate, and cracks are for me through the coarse aggregate. Observation by Varghese et al.[56]confirms this because in their investigation safe cracks were noted across the aggregate.
Singh,L.P et al., 2019[24]	FAC	Powder	This is why the strength of the gel concrete at 2%nSat28and91days was not further increased. Concrete containing 30,40, and 50% FA and 3% nS tested for compressive strength. The maximum strength was demonstrated by concrete with 30% FA plus 3% nS (30FA3nS). Compared to the 30FA3nSblend, concrete samples with 30% FA plus 6%SF showed a slight improvement in strength.

			w/b=0.29.
Nazari et. al., 2011[70]	GGBFSSCC	Powder 15nm	As nS content increased up to 3%, the compressive strength of concrete containing GGBFS increased. The duction of the concrete compressive strength at the nS particles of more than 3 might be due to the deficiency of hydrated lime w.r.t then Sparticles, which led excess silica to leach out and cause a deficiency in strength. w/b=0.4

(II) Tensile strength: -

Studies show that nS-applied concrete has a higher tensile strength in comparison to ordinary and mineral admixed concretes. Hasan-Nattaj et al. [44] reported that the tensile strength of steel-fiber reinforced concrete containing 2% nS was increased by 8.2% and 80.6%, respectively, relative to the fiber-reinforced concrete and plain concrete. The HPSCC exhibited a marked increase in splitting tensile strength through the inclusion of 2% nS and 10% SF, due to the high reactivity of nS to consume CH formed during the hydration [43]. It was observed by NajiGivi et al. [60] that the compressive strength, together with the tensile and flexural strengths of the nS blended cement concrete was high for all ages of moist curing up to 90 days compared to non-nS concrete, but the effect of nS with 80 nm size was more noticeable than that with 15 nm particles. The concrete with no particles of 10–140 nm sizeand up to 10% exhibited an increase in splitting tensile strength at 0.2 w/c ratio [63]. With an increase in nS content up to 3%, the split tensile strength of the concrete increased due to reduced voids in the mortar matrix and the formation of a strong ITZ [45]. The tensile strength of the polyethylene terephthalate (PET) composite concrete was increased by 25% and 48% relative to the reference concrete and PET composite concrete, respectively, by 3% nS inclusion [59]. The development of tensile strength in nS concrete at an early age was reported slightly high compared to the mS concrete, but both nS and mS concrete exhibited almost the same tensile strength at later ages [56]. Compared to the reference concrete at 87 days, the ultimate tensile strength of concrete containing 1% nS increased by 46%, but the strength improvement was reduced to 28% when 25% FA with 1% nSwas applied [76]. According to Hameed et al. [73], 2.5 to 10% CnS in SCC with 10% mS increased the tensile strength from 16.67 to 34.87%, respectively, compared to the SCC with 10% mS alone. The split tensile strength increased with nS content up to 3% in the GGBFS admixed SCC, and further addition of nS caused the strength to decrease, similar to the results of compressive strength [70]. High-strength concrete (HSC) containing 1.25% macro-polymeric (MP) fiber and 3% nS showed a 29% increase and concrete containing 0.1% PP, 0.9% MP, and

3% nS showed a 25% increase in strength. While the HSC containing only 3% nS showed an improvement of 16% tensile strength compared to plain concrete [69]. Compared to the reference concrete, the split tensile strength of HPC partially replaced with copper slag as fine aggregate exhibited an increase of 89, 33.2, 18.2, and 26.8% respectively at 1, 7, 28, and 90 days by adding 2% CnS. Whereas at 2.5% CnS, the increase in strength reduced to 78.5, 29.5, 15.5, and 21.5%, respectively at 1, 7, 28, and 90 days [65]. Kumar et al. [37] reported an improvement of 22% in tensile strength by replacing OPC with an optimal dose of 3% nS. With the addition of 1.2% nS particles the split tensile strength of 100% RA concrete reached close to the strength of the control mix with natural aggregate [87]. Mukharjee et al. [47] observed an increase of split tensile strength in RAC as nS content increased and that the tensile strength of RAC containing 3% nS was nearly equal to that of control concrete with natural aggregate, and this is because nS offered a denser and stronger interfacial transition zone (ITZ). Quercia et al. [49] also reported that the bond between hardened paste and aggregate strengthened by nS increased the tensile strength in concrete. A comparison of the tensile strength of concrete with 3% nS at 0.4 w/c ratios at 7, 28, and 90 days is given in Fig. 5. Fig. 6 shows 28 days of tensile strength in different concretes at different nS dosages. The details of the studies are provided in Table 3.

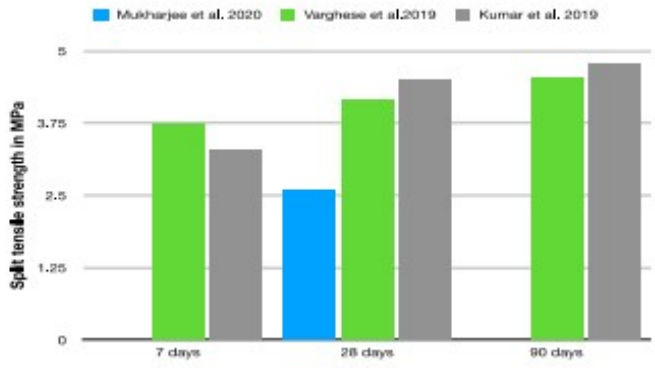


Fig.2.3. Split tensile strength of concrete with 3% nS and 0.4 w/c ratio.

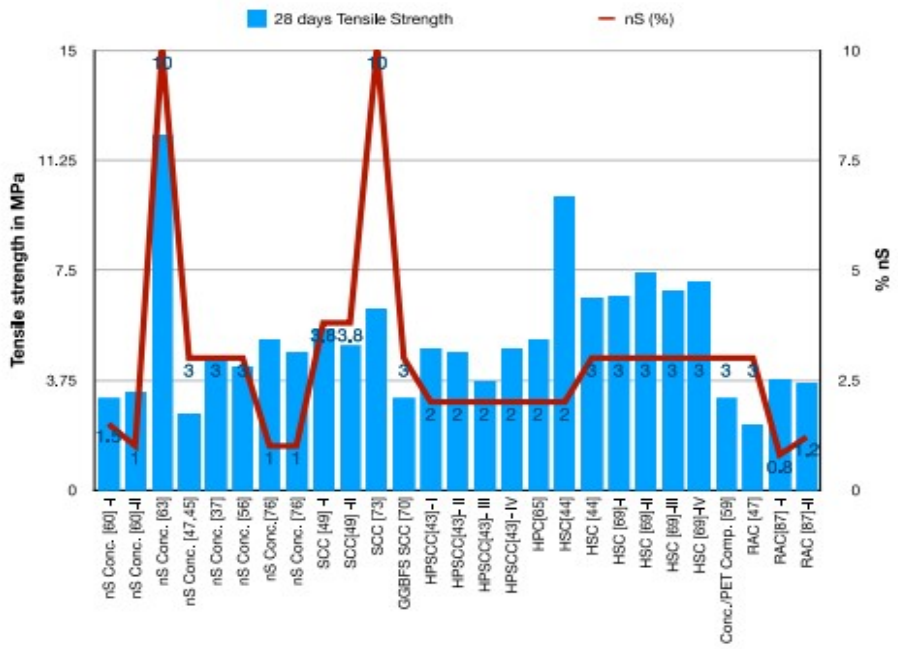


Fig.2.4. Tensile strength of different types of concrete at different dosages and w/c ratios at 28days

Table 2.3: -

The effect of nS on the tensile strength of different types of concrete.

Reference	Type of concrete	Type and Size of nS	Remarks
Najigivi et al.,2010[60]-I	Concrete with nS	Powder 15nm	Upto 2 percent inclusion of nS particles increased the splitting tensile strength. The optimal level of nS replacement were1and1.5% for 15 (fine Ns) and 80nm (Course nS) particles, respectively.
Najigivi et al.,2010[60]-II	Concrete with nS	Powder 80 nm	With an ncrease in nS particles upto10%, the splitting tensile strength increased. A strong correlation between split tensile strength and compressive strength was observed. w/c=0.2
Saloma et al.,2013[63]	Concrete with nS	Powder 10-140 nm	The pozzolanic activity and filler effects of nS particles improved the split tensile

			strength. Less voids and strong ITZ contributed high tensile strength tons added mix. w/b=0.4
Mukharjee et al., 2014,2020[47,45]	Concrete with nS	Colloidal 8–20nm	An optimum dosage of 3% is observed for maximum tensile strength development. Even at a 5% nS dose the splitting tensile strength was higher than that of the reference concrete. The enhancements in spiliting tensile strength were due to pozzolanic action and nS particle filler effects that made the concrete stronger and densor. w/c=0.4
Kumar et al.,2019[37]	Concrete with nS	Powder	The development of high early age splitting tensile strength in nS concrete was similar to that in compressive strength. After 28days, the difference in split tensile strength of nS concrete and mS concrete was small. An increase of 44% in tensile strength, compared to reference concrete, was observed in nS concrete with 3% nS. w/b=0.4
Varghese et al., 2019[56]	Concrete with nS	Powder 40–50nm	An increase of 45 and 32% in divide tensile strength was observed for concrete with 1% nS and concrete with 25% FA plus 1% nS, respectively, on the 29th day. w/b=0.5
Sivasankaranet.al., 2019[76]	Concrete with nS	Powder50nm	An increase of 45 and 32% individe tensile strength was observed for concrete with 1% nS and concrete with 25% FA plus 1% nS, respectively, on the 29th day. w/b=0.5

Sivasankaranet.al., 2019[76]	Concrete with nS	Powder50nm	The average split tensile strengths of concrete with powdered and colloidal nS were 5.48 and 4.92N/mm^2, respectively, and higher than the tensile strength of 4.51N/mm^2 observed in reference concrete. w/b=0.43
Quercia et al.,2014[49]-I	SCC	Powder	The average split tensile strengths of concrete with powdered and colloidal nS were 5.48 and 4.92N/mm^2, respectively, and higher than the tensile strength of 4.51N/mm^2 observed in reference concrete. w/b=0.43
Quercia et al.,2014[49]-II	SCC	Colloidal	-

(III) Flexural strength: -

The studies by Jalal et al. [43] reported that the HPSCC containing 2% nS and 10% SF showed higher flexural strength compared to control concrete with a maximum increase of 59% at 28 days; however, the rate of developing flexural strength was seen to be decreased at later ages. They further reported that the flexural strength of the concrete containing nS alone was comparatively less than that of nS plus SF admixed concrete. According to NajGivi et al. [60], nS particles enhanced flexural strength at all stages of curing up to 90 days without much variation in the rate of strength development. The study further identified that at 90 days, concrete containing nS with 80 nm diameter exhibited a higher flexural strength compared to concrete with 15 nm dia. nanoparticles. The flexural strength declined by incorporating PET particles in the composite concrete was improved by nS particles due to the improved adhesion between the contact area of the cement paste and aggregate, as reported by Behzadian et al. [59]. Elrahman et al. [48] observed an improvement of early flexural strength in LWAC, with a limited improvement noticed for a lower dose of nS; however, no dosage above 1% effectively enhanced the flexural strength at 28 days. NajiGivi et al. [78] noticed that the flexural strength of

the water-cured specimens increased with the substitution of up to 1% nS, and then decreased as nS increased, however, in the specimens cured in the solution of lime the flexural strength was improved for nS up to 2% replacement. According to Mukherjee et al. [47], the addition of 3% nS into RAC compensated for the decline in the flexural tensile strength as a result of the replacement of natural aggregate (NA) with recycled aggregate (RA) and a 15% increase in flexural tensile strength at 28 days was also observed in both NA and RA concretes due to nS addition. According to Li et al. [38], compared to the control UHPC matrix, adding 1% nS exhibited approximately 41 and 35% higher flexural strength for UHPC under the combined curing conditions of 2 days of heat and 26 days of standard curing, at 0.16 and 0.17 w/b ratios, respectively. Adding more than 1% nS, however, resulted in a lesser flexural strength improvement. Fig. 7 shows the effect of nS with its different dosages at 28 days on the flexural strength of various concrete samples. The findings on the effect of nS on flexural strength in concrete are summarised in Table 4.

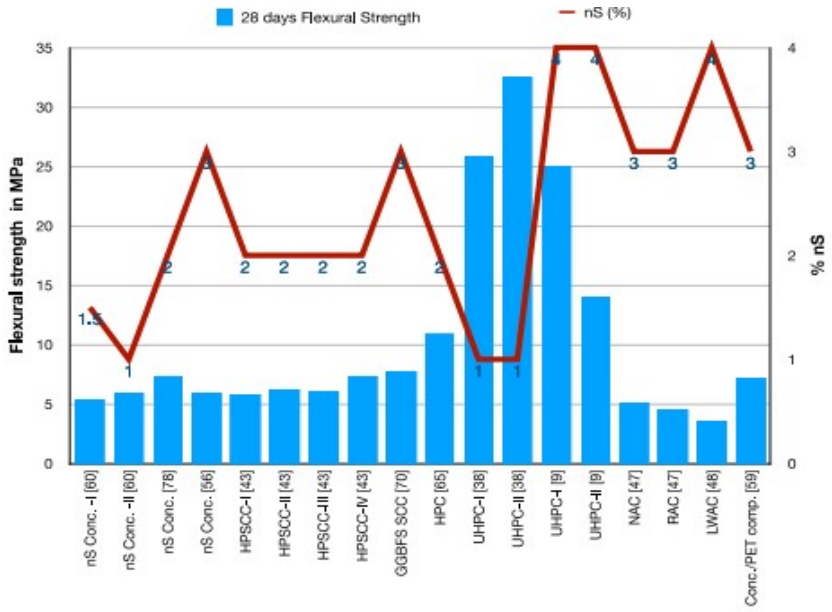


Fig. 2.5. Flexural strength of different types of concrete at different nS dosages and w/b ratios at 28 days

Table 2.4: -

The effect of nS on flexural strength of different types of concrete.

Author	Type of Concrete	Type and size of nS	Remarks
Najigivi et al.,2010[60]	Concrete with nS	Powder15nm	Upto 2 percent inclusion of nS particles increased the flexural strength. The optimal level of nS replacement were 1 and 2% for 15 and 80 nm particles, respectively. w/b=0.4
Najigivi et al., 2010[60] -II	Concrete with nS	Powder 80nm	Upto 2 percent inclusion of nS particles increased the flexural strength. The optimal level of nS replacement were 1 and 2% for 15 and 80 nm particles, respectively. w/b=0.4
Najigivi et al., 2010[78] -I	Concrete with nS	Powder 15±3 nm	Ord. Conc., curedin lime solution Similar to the compressive strength, the flexure strength of the samples curedin lime solution washig were compared to water cured samples[60]. The optimum dose of nS was 1% to improve the mechanical properties of the water cured samples, while that was 2% for lime cured samples. In the presence of lime solution, the formation of CSH gel was higher as the amount of nS present was close to the amount needed to combine with

			libe rated lime during the hydration process, resulting in less leaching of silica compared to water cured samples. w/c=0.4
Varghese et al., 2019[56]	HPC	Powder 25 nm	The flexural strength is influenced by the compactness of ITZ obtained by the application of nS particles. Atallages, the flexural strength of nS-HPC surpassed that of both mS-HPC and reference concrete, indicating that nS particles strengthen the ITZ. w/c=0.4
Jalal et al.,2015[43]-I	HP SCC 400- nS 2%	Powder 15±3	Cement replacement by 10% SF plus 2% NS improved the flexural strength for binder content of 400 and 500 by 23.5, 58.9 and 47% and 20, 52 and 52% respectively at 7, 28 and 90 days compared to control specimens. Water binder ratio (w/b)=0.38
Jalal et al., 2015[43] -II	HP SCC 400-nS 2%	Powder 15±3	Cement replacement by 10% SF plus 2% NS improved the flexural strength for binder content of 400 and 500 by 23.5, 58.9 and 47% and 20, 52 and 52% respectively at 7, 28 and 90days compared to control specimens. Water binder ratio (w/b)=0.38
Jalal et al.,	HP SCC	Powder 15±3	Cement replacement by 10% SF plus

2015[43] -III	500 500-Ns 2%		2% NS improved the flexural strength for binder content of 400 and 500 by 23.5, 58.9 and 47% and 20, 52 and 52% respectively at 7, 28 and 90 days compared to control specimens. Water binder ratio (W/B)= 0.38
Jalal et al., 2015[43] -IV	HP SCC 500-SF 10%	Powder 15±3	Cement replacement by10% SF plus 2% NS improved the flexural strength for binder content of 400 and 500 by 23.5, 58.9 and 47% and 20, 52 and 52% respectively at 7, 28 and 90 days compared to control specimens. Water binder ratio (w/b)=0.38
Nazari et al., 2011[70]	GGBFS SCC	Powder 15nm	. The flexural strength was high compared to the reference concrete for all nS incorporated concrete due to the increased formation of hydration product in the presence of nS nano particles. w/b=0.4
Chithra et al., 2016[65]	HPC	Colloidal 5 to 40 nm	Compared to reference concrete, the improvement of flexural strength at 7days was 11.7, 20.1, 29.3, 37.7, 33.2 and 27.6% for 0.5, 1, 1.5, 2, 2.5 and 3% nS respectively and at 28 days the improvement was 10.7, 21.1, 28.8, 36.5, 29.2 and 22% respectively. w/b=0.31

(IV) Modulus of elasticity: -

Saloma et al. [63] observed a higher elastic modulus in nS concrete compared to non-nS concrete, indicating that the stiffness of nS concrete is greater than that of non-nS concrete. According to Durgun et al. [88], the increase in stiffness was associated with the efficient densification of the interface between the aggregates and the hardened cement matrix by the addition of nS, resulting in a stronger bond between them. The latest research showed only the slightest increase in the elastic modulus of concrete while adding the nS particles up to 3% [45]. However, Belkowitz et al. [61] observed a higher elastic modulus in concrete with smaller (5 nm) nS particles at lower doses and with larger (16 and 46 nm) particles at higher doses. Belkowitz's study also showed that the smallest particles of 5 nm nS at its lowest dosage generated the highest modulus, which is a 20% increase over OPC and 22% over concrete with 20% FA, indicating that the size of the nS and its surface area is sensitive to the mechanical properties of the concrete. Other investigation on FA concrete [76] showed that incorporating 2% nS increased the elastic modulus of FA (25% of cement as replacement) concrete by 134% on the 87th day, but for concrete containing only nS, the increment was 167% compared to the reference concrete. It is interesting to note that the elastic modulus of the concrete with 25% FA alone on the 87th day and for concrete with 2% nS plus 25% FA on the 29th day was the same [76]. Hasan Nattaj et al. [44] reported that due to the increased compactness of the bond between cement paste and aggregates, as reported by [63], the nS and SF in the fiber-reinforced concrete (FRC) improved the elastic modulus. Mukherjee et al. [45] reported an improvement in concrete density by adding nS relative to the reference mix, showing the compactness of the nS-added concrete. In the studies conducted on SCC with colloidal nS, the optimum elastic modulus was reached at 2.5% CnS content [73]. Fallah et. al. [69] reported a significant influence of nS on the initial and second modulus of elasticity of HSC, and at 2% nS, the modulus of elasticity reached its maximum value. Erdem et al. 2018 [86] reported an increase in dynamic elastic modulus in RAC, due to improved microstructure, with an increase in the amount of nS. The effect of nS at 28 days on the elastic modulus of different types of concretes is shown in Fig. 8. Table 5 summarises the results on the influence of nS on the elastic modulus of concrete.

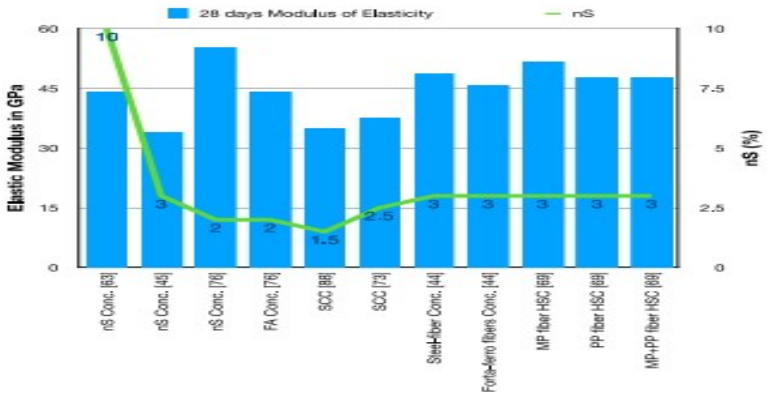


Fig.2.6. Elastic modulus of different types of concrete at different nS dosages at 28 days.

Table 2.5: -

The effect of nS on the elastic modulus of different types of concrete

Reference	Concrete	Type and size of nS	Remarks
Saloma et al , 2013 [63]	Concrete with nS	Powder 10 140 nm	The average elastic modulus of concrete with nS was observed greater than that of concrete without nS. Due to the improved compactness of cement paste-aggregate bond in nS concrete, compared to concrete without nS, the nS concrete had a higher stiffness.
Durgun et al., 2018[88]	SCC	Colloidal 5, 17, 35 nm	Among 5, 17, 35 nm nS particles. 35nm size particles showed effective in improving the elastic modulus in concrete with FA.
Mukharjee Et al., 2020 [45]	Concrete with nS	Colloidal 8–20 nm	With the addition of 3% nS, the change in elasticity modulus (E) was not significant as it showed only a 4% increase in compared to the reference

			mix.
Sivasankaran et al., 2019[76]	Concrete with nS. nS + 25% Fly ash conc.	Powder 50 nm	By adding 2% nS, the elastic modulus was enhanced in all concrete mixes in which the FA content ranged from 25 to 75 percent, as well as in concrete without FA. At 29 days, the increase in elastic modulus was not significant, but at 87days, it was increased by 167% for concrete with 2% nS without FA and by 167, 134, 127% for concrete with 2% nS and 25, 50, and 75% FA content, respectively.
Hasan-Nattaj et al., 2017 [44]	1%Steel Fiber + 3%nS 0.5% Forta-ferro fiber + 3%nS	Powder 20–30 nm	nS in concrete reinforced with steel and forta-ferro fibers increased the elastic modulus, with the increase was more significant for steel fibers. Incorporating nS particles resulted in an increase in the compactness of the cementpaste-aggregates bond, which in turn increased the stiffness of the concrete, thus improving the elastic modulus.
Hameed et al., 2020 [73]	1.25% MP+3%nS	Colloidal	Small increase in the elastic modulus relative to reference concrete. Maximum elastic modulus was observed at 2.5% nS dosage; however, the maximum compressive strength was observed at 10% nS
Fallah et al., 2017[69]	0.2% PP + 3% nS 30.1% PP + 0.9% MP+3%nS	Powder 20–30 nm	By using the nS particles as a cement replacement, the elastic modulus of concrete increased relative to the plain concrete.With 2%nS the high-

			strength concrete with PP and MP fiber sexhibited high initial and secant modulus of elasticity.

(V) Abrasion resistance: -

Nazari et al. [79] reported that replacing Portland cement with nS particles up to 2 wt% increased the resistance of abrasion of the concrete, and a higher rate of increment was seen for the higher dose of nS for both water and lime water-cured specimens. Chithra et al. [65] also noted that the abrasion resistance increased by the

use of nS up to 2% in high-performance slag concrete (HPSC), whereas a slight decrease in abrasion resistance was observed at 2.5 and 3% nS. For the concrete containing 1% nS, the surface and side indices of abrasion resistance increased by 157% and 139%, respectively [62]. Shamsai et al. [89] observed the influence of the w/c ratio on abrasion resistance in nS concrete and recorded a 36% increase in abrasive strength when the w/c ratio decreased from 0.50 to0.33. Cheng et al. [90] reported a reduction in abrasion loss of nS concrete compared to non-nS concrete by 36.4, 39.1, and 44.4% for 7, 28, and 84 days, respectively.

(VI) Impact resistance: -

Erdem et al. [86] reported that the addition of nS to the RAC increased its impact resistance. Though the number of blows for the formation of the first crack did not correlate to the amount of nS added, the number of blows for the ultimate failure increased as the nS content increased. According to Erdem et al., this is due to the reduced pores in concrete with enhanced pore structure at its microscopic level by the application of nS and the consequent stimulation of the toughening mechanism and crack deflection.

(VII) Compressive stress-strain behavior/ stress-strainrelationship: -

According to Fallah-Valukolaee et al. [91], adding nS to the hybrid fiber concrete contributed to an increase in the ultimate strain. The study reported that the strain at peak stress increased in the fiber-reinforced concrete with nS compared to that in the concrete lacking nS. The study also concluded that the effect of nS on the ultimate strain was more significant than that of SF in synthetic fiber-reinforced concrete. Nematzadeh et al. [92] reported that the use of nS resulted in a lower strain at peak stress in the steel fiber-reinforced concrete compared to the non-nS steel-

fiber reinforced concrete, whereas this effect of nS was negligible in forta-ferro fiber-reinforced concrete. In the above investigation, it was also revealed that the incorporation of nS into the FRC improved its ultimate strain, with higher ultimate strains for higher nS replacement rates. Also, for both steel and forta-ferro FRCs, as the replacement rates of nS increased, the concrete carried greater normalized stress at a particular strain, resulting in a higher area under the stress-strain curve. As the compressive strength increased by the use of nS and/or mS in concrete, the axial stress-strain curve became steeper at both the pre-peak and post-peak stages, indicating higher stiffness and lower ductility [93].

(VIII) Non-destructive parameters: -

According to Mukherjee et al. [45], the ultrasonic pulse velocity (UPV) and rebound number (RN) values increased in the concrete mix with an increase in the nS content, indicating that the concrete quality ameliorated from good to excellent with the addition of nS particles.

2.4. Effect of nano-silica on durability parameters: -

(I) Pore structure/porosity: -

Several researchers noted a significant reduction in porosity and improvement in the concrete pore structure while applying nS to concrete. According to Zhang et al. [41], the large capillary porosity decreased with the increased dosage of nS as well as the threshold, and critical diameters of the pores were found to have decreased at 2% nS. Said et al. [84] reported that due to the filling and high pozzolanic actions of nS particles, the threshold pore diameter was reduced with a corresponding increase in the percentage of small pores (micro-cracks) in concrete with and without FA, which was significant at 6% dosage of nS compared to 2%. The addition of nS significantly reduced the increased pore size and total porosity resulting from the replacement of cement by FA [83]. Ghafari et al. [42] reported that the pore structure was refined in UHPC due to the pores being filled by the additional hydration products resulting from the high pozzolanic reactivity of silica nanoparticles. According to Sivasankaran et al. [76], the inclusion of 2% nS reduced the porosity in the cement paste by filling the micropores and thus increased the pore size distribution. Alhawat et al. [55] found that the volume of pores in concrete containing nS with small surface area (bigger particles) was relatively high as they were prevented from occupying the pores; however, the concrete containing 3% of nS with large surface area (smaller particles) exhibited a more densified concrete microstructure rich with CSH and remarkably less capillary pores. Belkowitz et al. [61] stated that the agglomeration of the small particles of nS caused voids to form in concrete at their high dosage, resulting in high

concrete porosity. Du et al. [77] reported that the porosity of the LWC with 1% nS was reduced due to a more compact and homogeneous microstructure developed by the filler effect and pozzolanic action of the nS particles. According to Du et al. however, more than 1% nS, which increased the viscosity of the cement paste, allowed more air voids to entrap into the concrete mixture during mixing, and the porosity of the hardened concrete could be increased if the densifying effect of the nS particle is not sufficient to compensate for this increased air content. However, Elrahman et al. [48] reported that due to the increased solid content between the voids, the replacement of 4 wt% nS in LWC reduced the pore diameter and the volume of porosity to 39.53 vol% from 54.38 vol% of the reference concrete. The nS particles improved the pore structure of SCC and increased the content of all mesopores and macropores [70].

(II) Water absorption, sorptivity, water permeability, and infiltration rate: -

Ghafari et al. [42] reported that adding nS resulted in reduced absorption of water and sorptivity in UHPC relative to the reference concrete mix, indicating that the connection between the capillary pores was significantly reduced due to the pores filled with the additional hydration products formed by high pozzolanic reactivity of nS. This was similar to the findings of Du et al. [77], who observed a 35% reduction in the initial setting time and 32% in secondary sorptivity in pure cement LWC by using 2% nS, an optimum dose for pure cement, as an additive. However, the initial and final sorptivity again reduced to 73 and 83% respectively in slag cement LWC by the use of 1% nS, an optimum dose for slag cement, as an additive which could be attributed to the insufficient densifying effect of nS at its higher dosage to compensate the increased air content and subsequent development of more pores in hardened concrete. According to Atmaca et al. [67], the sorptivity of 3% nS HSLWC decreased by 25% compared to the reference concrete with the same replacement level of LWA. As reported by Elrahman et al. [48] 4% nS showed a beneficial effect on LWC to reduce porosity and water absorption. The presence of nSwasfound to have reduced the water absorption in hardened high-strength concrete with macro-polymeric (MP) and polypropylene (PP) fibers and the least value of absorption was observed at 3% nS [69]. Younis et al. [87], observed that in RAC the water absorption decreased by 11% at a small nS dosage of 0.8% compared to control concrete. An investigation by Isfahani et al. [82] revealed that 0.5% nS, as a cement replacement, had a negligible effect on water absorption and sorptivity in concrete with 0.65 w/b ratios however, they were found to reduce at 0.55 w/b ratio with 1% nS. Kumar et al. [37] reported a 36.84% decrease in water absorption in concrete added with 3% nS compared to the normal concrete, stating that the highly reactive nS formed more CSH gel and packed the voids of the concrete matrix. The permeability decreased with an increased nS dosage and the maximum reduction of 51.5% in permeability compared to the control mix reached 4.5% nS [64]. Erdem et al. [86] also reported a similar effect of nS in RAC as the nS in concrete improved its porous structure. Rezania et al. [94] reported that the permeability reduction experienced a decreasing trend with the increase in nanoparticle content

due to the difficulty of their dispersion in concrete at their higher dosage. In alkali-activated slag (AAS) concrete, the use of nS contributed to an undesirable rise in water penetration depths; however, the use of mS reduced the permeability [95]. Compared to concrete containing nS, the decrease in water absorption in fiber-reinforced concrete with SF was more noticeable, according to Hasan-Nattaj et al. [44]. The result obtained by Jalal et al. [43], on the other hand, showed that water absorption in HPSCC was further reduced by the inclusion of 2% nS with 10% SF due to the efficient packing and refinement of concrete micro and pore structures achieved through the combined effect of nS and SF. Due to its more refined pore structure, water absorption in concrete with nS was reduced by 6.4% and 18.3% compared to concrete with mS and reference concrete [96]. Najigivi et al. [97] reported that rice husk ash (RHA) mixed concrete with 15 nm nS significantly enhanced water absorption resistance at 28 days; however, after 90 days, a higher resistance was observed in concrete with 80 nm nS. Tawfik et al. [98] found the lowest water penetration in HPC consisting of 3% nS compared to the HPC incorporated with nanoparticles of silica fume, fly ash or coal. Mohammed et al. [99] reported that the nS particles induced fly ash reaction and decreased the roughness of the inner surface of the voids, which in turn caused an increase in infiltration in the pervious concrete. For a good previous concrete, it is favorable to have a better infiltration rate. Water absorption of different types of concrete added with nS is illustrated in Fig. 9. The particulars of water absorption of nS-added concrete are given in Table 6.

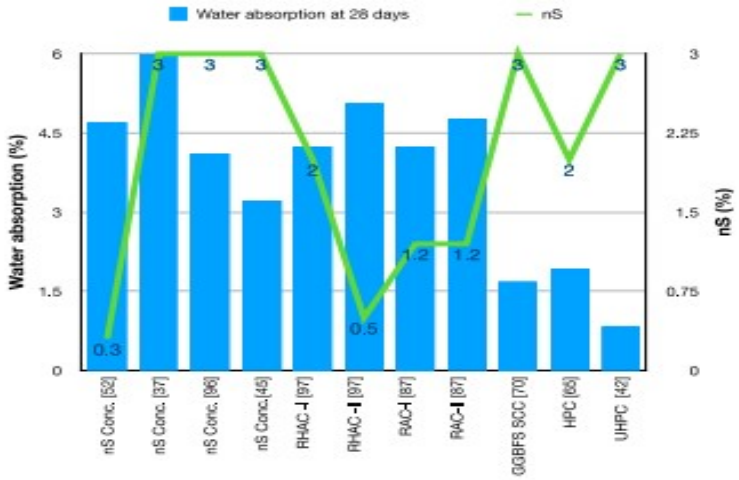


Fig. 2.7. Water absorption of different types of concrete at different nS dosages at 28 days

Table 2.6: -

The effect of nS on water absorption in different types of concrete.

Reference	Type of concrete	Type and size of nS	Remarks
Najigivi et. al.,2012[97]	Fine nS RHAC 15 nm	Powder 15nm	At 2% nS, the lowest WA of 2.08% was observed in concrete with 80 nm at 90 days.
Najigivi et al.,2012[97]	CoursenS RHAC 80nm	Powder 80nm	Concrete containing 80 nm nano particles showed improved water absorption resistance after 90 days of curing, while15 nm nano particles showed improved resistance to concrete water absorption after 28days of curing.
Lincy et al., 2017[96]	Concretew ith nS	Colloidal 40–50 nm	Concrete with nS particles exhibited the lowest water absorption compared to microsilica(mS)andreferenceconcr etesby6.4%and18.3%,respectively.
Mukharjee et al., 2020[45]	GGBFS SCC	Colloidal–20 nm	The WA of the concrete was reduced with the increase in nS content owing to thereduced voids in the concrete by the presence of nSparticles. The water absorbing potential of the concrete mix was consequently reduced.
Nazari et al., 2011[70]	HPC with copper Slag as	Powder15n m	Compared to GGBFS concrete with nS particles, the WA in GGBFS concrete

	fine aggregate		without nS showed a lower WA at 7days. However, at 28 and 90 days, the water absorption was lower for GGBFS with nS particles. This can be attributed to high formation of hydration products in nS added GGBFS concrete during early age curing
Chithra et al., 2016[65]	RACRA 50% nS 1.2% RAC RA 100% nS1.2%	Colloidal 5 to 40 nm	Due to the combined action of the pore filling effect and acceleration of hydration of nS the water absorption and sorptivity values of HPSC decreased with an increase in nS particles, making the concrete denser and more compact. Maximum decreases in water absorption and sorptivity values were observed with 2% nS in HPSC.
Younis et al., 2018[87]	Concrete with nS.	Powder 20–30 nm	The effect of adding 0.4% of nano particles to the WA was negligible for both RA contents (50% and 100%), while adding 0.8% of nS contributed to a decrease of 10 and 11% in the WA of RAC mixes with 50 and 100% RA contents, respectively.
Du et al., 2014[52]	Concrete with nS.	Powder13nm	Due to the refined pore structure and decreased connectivity of capillary pores in nS in corporate mixes the rate of WA in the concrete was reduced. The nS slightly modified the initial water sorptivity, water absorption and water accessible porosity.

Kumar et al., 2019[37]	Concrete with nS	Powder With surface area of 22000 m^2/kg	The minimum WA, 6 and 5.6% respectively at 28 and 90 days, was found in concrete with 3% nS particles. This is 37% less than the WA of control concrete.
Ghafari et al., 2014[42]	UHPC	Powder 15±5 nm	Incorporating 1, 2, 3, and 4% nS into Concrete resulted In a decrease of WA by 8.5, 21, 33, And 29%, respectively.

(III) Chloride ion penetration: -

Mercury Intrusion Porosimetry (MIP) tests results confirmed that the filler and pozzolanic actions of nS reduced the rate of water and chloride ion penetration even at a low dose of 0.3% nS [52]. A similar observation was made by Isfahani et al. [82] showed that the chloride diffusion coefficient reduced at 0.5% nS dosage with w/b ratios of 0.55 and 0.65; however, at a higher dosage of nS, such reduction was not noticed. The reduction of charge passed within the slag concrete was found to be in agreement with the reduction in the critical threshold diameter of pores and refined microstructure due to the inclusion of nS [34]. Although the porosity was higher in LWC at 2% nS, the higher binding capacity of CSH gel formed interrupted the chloride ion transport [77]. The reduced conductivity in concrete with a small dose of nS resulted in lower chloride ion penetration in the cementitious matrix [84]. The resistance to penetration of chloride ions in the nS concrete was relatively high compared to mS and reference concretes [96]. However, Jalal et al. [43] revealed that using nS and SF together in HPSCC reduced chloride ion penetration significantly.

(IV) Sulphate attack: -

The concrete specimens with 3% nS immersed in sewage water for 90 days showed the lowest reduction in compressive strength due to sulphate attack [98]. This indicates that the nS particles are very effective in resisting sulphateattacks in concrete.

(V)Carbonation: -

According to Singh et al. [24], the use of 3% nS in FA concrete significantly reduced the depth of carbonation by 73% after 180 days of exposure in comparison with its control mix, while FA concrete with SF showed a reduction of only 35% in the same exposure condition. It is due to the hydration products produced in the presence of nS being more stable and resistant to the penetration of aggressive ions, which would benefit the more extended durability of FA concrete. Kumar et al. [37] reported that the inclusion of nS up to 3% decreased the carbonation depth by 46 and 17% at 7 and 70 days, respectively, compared to ordinary concrete, whereas a further increase of nS increased the carbonation depth with the time of exposure. The authors hypothesized that this is due to the excess CH reacted with nS to form CSH gel, and at a 3% dose of nS, a dense matrix was obtained, and further addition of nS did not contribute to making a denser concrete. While Isfahani et al. [82] reported that the addition of nS resulted in a detrimental effect on carbonation as the carbonation coefficient was observed to increase from the reference of 24 to 29.3 mm/year at 1% nS for 0.65 w/b ratios, however for 0.55 w/b ratio with the same number of nS the carbonation coefficient was reduced from the reference of 20.4 to 16 mm/pyear. Also, according to Behfarnia et al [95], due to increased CO2 penetration, the inclusion of nS particles in AAS concrete caused an increase in carbonation depth.

(VI) Corrosion resistance: -

Compared to the other nanoparticles, nS with a 3% optimum level was found to have improved the durability and reduced corrosion rate in HPC. The depth of corrosion was reduced by 37.8, 58.5, and 67.5% at 3 months for the HPC incorporated with 1, 2 and 3% nS compared to the control sample, and a similar trend was also observed after 6 months [98].

(VII) Temperature effects: -

Elkady et al. [64] reported an initial compressive strength loss of approximately 30, 16, 25, and 22% in the indirect fire test at temperatures between 0 C and 400 C at 0, 1.5, 3, and 4.5% nS respectively. However, these losses were 49, 27, 37, and 62% for the temperature range between

400 C and 600 C. In the temperature range between 0 C and 400 C, the specimen was found to have lost approximately 37, 29, 49, and 26% of its initial bond strength respectively at 0, 1.5, 3, and 4.5% nS dosages. While in the temperature between 400 C and 600 C, the above respective losses were approximately 84, 65, 79, and 86%. The study cited that initial loss of strength at the temperature between 0 C and 400 C was due to loss of cohesive force between the layers of CSH gel, while the loss of strength at the higher temperature, i.e. between 400 C and 600 C, was attributed to the severe vapour pressure developed in the dense pores of the concrete which caused the spalling and cracking of the concrete. The thermogravimetric investigation by [70] in the range of 110–650 C showed dehydration of the hydrated products and increased loss of weight, after 90 days of curing, of the specimens with nS particles upto 3% in GGBFS incorporated SSC. The spalling and mass loss experienced in nS admixed HSC when the specimen heated more than 400 C, but this was observed just above 300 C for HSC without nS [85].

(VIII) Frost resistance: -

Experimental studies of Cheng et al. [90] in cold regions of China showed that applying nS to concrete improved the frost resistance of bridge deck pavement. The concrete mass loss rate in nS concrete was lower than in non-nS concrete for up to 300 freeze-thaw cycles, and the loss rate decreased with an increase in cycles in both non-chloride salt and chloride salt environments. Similarly, according to Cheng et al., the dynamic elastic modulus in nS-applied concrete was also high and increased with an increase in the freeze-thaw cycle. Massana et al. [74] also noted an enhancement in freeze-thaw resistance in HPSCC with nS.

(IX) Effect of acid exposure: -

The compressive strength of the nS-incorporated specimen exposed to sulfuric acid rain showed a higher compressive strength compared to the reference specimen. This is due to the reduced porosity in the concrete by the filling effect of nS and the improved bonding between aggregates and hydrated cement paste in the presence of nS [100]. The study also found that the percentage of weight loss of concrete specimens decreased with increased nS content in acid exposure. The electrical resistance of concrete specimens also increased by adding more nS due to the high concrete compactness and pore solution composition change. However, according to [101], compared to the use of nS, SF in high-strength forta-ferro fiber (HSFF) concrete resulted in greater improvements in the durability of specimens exposed to the acid environment. The HSFF concrete specimen with 2% nS exhibited a high reduction in ultrasonic pulse velocity (UPV) compared to the 10% SF incorporated specimens, during its immersion in sulfuric acid up to 63 days. Furthermore, the above study showed a lower weight loss of the specimens, indicating less erosion in the acid exposure, with a high replacement level of 10% SF relative to the low replacement level of 2% nS. This is due to the lower potential of gypsum and ettringite

production in the concrete specimens containing 10% silica fume. The higher SF replacement level compared to the lower nS replacement level also led to a greater crushing load loss to the weight loss ratio.

2.5. Fracture behavior: -

The fracture behavior of the concrete is characterized by parameters such as fracture energy, fracture toughness, fracture process zone, and critical effective crack-tip opening displacement [102]. The fracture energy (Gf) increased as the colloidal nS content increased up to 3%, then decreased for further addition of colloidal nS [103] in self-compacting semi-lightweight (SCSL) concrete and the sample with less w/b ratio displayed higher fracture energy. It was reported that the fracture energy increased as compressive strength increased. The fracture toughness (KIC) of SCSL concrete increased as nS increased up to 3% and then decreased as in the case of fracture energy, and KIC increased by 24% as the w/b ratio decreased from 0.45 to 0.35. The fracture process zone (FPZ) was also influenced by the content of the colloidal nS and water binder ratio. The FPZ length (Cf) increased as nS content up to 3% and then decreased. However, the Cf decreased by 26% while the w/b ratio increased from 0.35 to 0.45 [103]. However, Zhang et al. 2015 [104] reported that the fracture parameters increased as the nS content increased up to 5% and then began to decrease upon further addition of nS in the fly ash concrete composite.

2.6. Rate of hydration: -

The temperature variation of the concrete mixes measured by the maturity logger for 24 h after mixing showed a noticeable rise in temperature in nano-silica high-performance concrete (nS-HPC) compared to ordinary concrete and micro-silica high-performance concrete (mS-HPC), indicating that nS particles increased early hydration in concrete. The peak increase of temperature in nSHPC was due to the formation of CSH gel by hydration of tricalcium silicate (C3S) 4 to 5 h earlier than that in ordinary concrete and mSHPC [56]. It was also reported by [41] that compared to SF, nS with its mean particle size of 7 and 12 nm was found more effective in increasing the hydration rate and reaction in high-volume slag cement (HVSC) concrete. Zhang et al. [41] observed that the dormant time in the cement and the slag pastes was shortened by adding nS, and the hydration rate of high-volume slag cement paste was accelerated. The hydration acceleration of cement could be due to an increase in nucleation sites offered by the small particles of nS, and that of slag could be due to an increase in the formation of CH at an early age owing to the increased cement hydration [34,41]. The rise in nucleation sites and the increase of pozzolanic activity by adding nS increased the hydration heat in HVFA concrete [53,83]. Said et al.[84] stated that the ultra-fine nature of the nS was the reason for accelerating the hydration reaction kinetics in concrete. Nanosilica particles can serve as the nucleus in CSH

gel to bind particles of CSH gel structures tightly and thus can improve the consolidation and stability of the structure of the hydration products [96]. NajiGivi et al. [60] reported that the concrete with 15 nm nS particles had more CSH gel formed compared to 80 nm particles, at the initial days of curing, due to more nucleation sites offered by small particles of nS and subsequent hydration acceleration. However, contrary to the above findings, Belkowitz et al. [61] mentioned that the larger nS particles of a low surface area increased the temperature of the hydrating cement more compared to the smaller nS particles with a higher surface area, suggesting that the greater stability and higher effectiveness of the larger nS particles which are less prone to agglomeration compared to the smaller ones. Du et al. [77] reported that adding 2% to slag cement paste did not further increase the overall heat after 72 h compared to the slag cement paste added with 1% nS. According to Ghafari et al. [42], incorporating nS particles into the cement paste containing very low w/c can enhance the formation of the hydration products and thus reduce the volume of portlandite.

2.7. Setting time: -

Cement was replaced by nano-silica with 3% and 5% by weight. Nano-silica increased the compressive strength of cement mortar. The effect of nano-SiO2 was found different for consistency and setting time. It made the cement paste thicker and accelerated the hydration of cement. It was reported that the effective water-to-binder ratio reduced the amount of water present in the mix [4]. This paper aimed to measure the influence of nano-silica on the hydration and strength improvement of cement paste. Cement was replaced by nano-silica with 1.5, 3, and 5% by weight. It was found that the NS induced the accelerated hydration of cement. The addition of NS reduced the slump considerably. Nano-silica played an important role as a pozzolanic reactant, but the pore solution remained highly alkaline even at 5% nano-silica content [5].

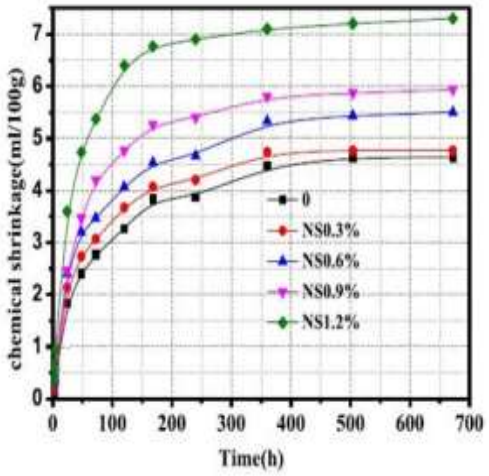
2.8. Workability of concrete:

The author studied the effect of nano-silica on mechanical properties, drying shrinkage, and flowability of ultra-high-performance concrete. Cement was substituted by NS with 2.5% and 5% by weight. The addition of nano-silica enhanced the crushing strength and drying shrinkage. Whereas, the workability of fresh ultra-high-performance concrete was reduced considerably [6]. This paper studied the influence of nano-SiO2 on the workability of concrete. Cement was substituted by nano-silica with 0.8% and 3.8% by weight. It was found that the addition of nano-silica decreased the workability of concrete and ascribed to more surface area of NS as compared to cement [7]. The presence of nano-SiO2 negatively affected the workability of concrete. Nano-SiO2 was substituted in place of cement with 1, 2, and 3% by weight. It was concluded that the higher dosage of NS considerably reduced the slump of concrete [8]. This experimental study investigated the role of nano-SiO2 on the fresh and rheological characteristics of glass fiber-reinforced self-consolidating concrete with 2 and 4% of cement replacement by nano-silica. It

was reported that 2% and 4% of nano-SiO2 with the addition of glass fiber caused to decrease the workability. Torque resistance is enhanced with increasing nano-silica content [9].

2.9. Shrinkage and creep of concrete: -

In separate experiments, cement was substituted with nano and micro-silica with 3% and 7.5% by weight. The concrete with the NS showed higher shrinkage and creep than the control concrete and the concrete containing the micro-silica [10]. This research work investigated the strength and shrinkage of powder-based nano-silica concrete. Cement was substituted by nano-silica with 0.5, 0.75, and 1% by weight of cement. The addition of nano-SiO2 enhanced the bending tensile strength but led to a higher rate of shrinkage [11]. The influence of nano-SiO2 together with fly ash on fresh property and shrinkage of mortar was studied. Cement was substituted with nano-silica by 0.5%, and 3%, and fly ash was substituted in place of cement by 5% and 20% by weight. The addition of NS significantly reduced the slump of the mortar, but dry shrinkage improved [12]. This research work was conducted to study the role of nano-SiO2on the volume and chemical shrinkage of cement composite. Cement was replaced by NS with 0.3, 0.6, 0.9, and 1.2% by weight. The chemical shrinkage increased with increasing NS content. By considering 1.2% of NS content, the chemical shrinkage after 3 days and 28 days was found to be increased by 93.7%, and 57.5% respectively as shown in Figure 1. The volume shrinkage also increased with increasing nano-silica content as shown in Figure 2 [13]. The researcher measured the influence of nano-SiO2 on water permeability, abrasion resistance, and drying shrinkage. Nano-silica of particle sizes of 12, 20, and 40nm were utilized in this research work. Cement was replaced by nano silica with 9% weight. Nano-silica of size 40nm with 9% by weight imparted the highest resistance to abrasion and water permeability and minimum shrinkage. Nano-SiO2 with particle sizes of 12nm and 20nm together with silica fume experienced higher shrinkage as compared to 40nm size, and control concrete [14]. This research work was carried out to investigate the influence of nano-SiO2 on the drying shrinkage of concrete. Cement was substituted by nano-silica with 0.5, 0.75, and 1% by weight. It was reported that the addition of NS enhanced the 28-day drying shrinkage rate by 75.5, 127.1, and 163% respectively [15]. This experimental research work explored the effect of partial replacement of cement by nano-silica and palm oil fuel ash (POFA) on the drying shrinkage of cement mortar. Cement was substituted by NS with 1%, and POFA with 10% and 30% by weight. It was found that POFA with a 30% replacement level enhanced water permeability by 138%, 158%, and 200% at the age of 3, 7, and 28 days. The replacement of POFA with 30% decreased the shrinkage but considerably reduced the compressive strength [16].



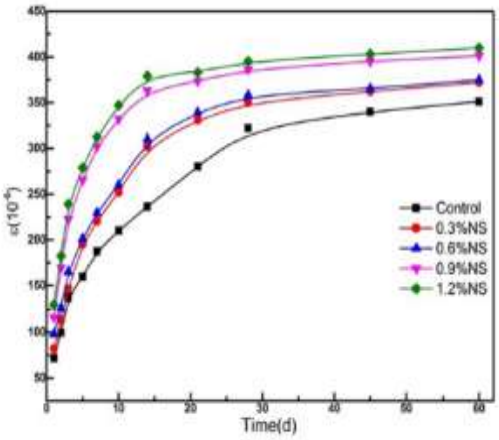


Fig. 2.8. Chemical shrinkage of cement paste [13]

Fig. 2.9. Volume shrinkage of cement paste [13]

2.10. Microstructural images of concrete: -

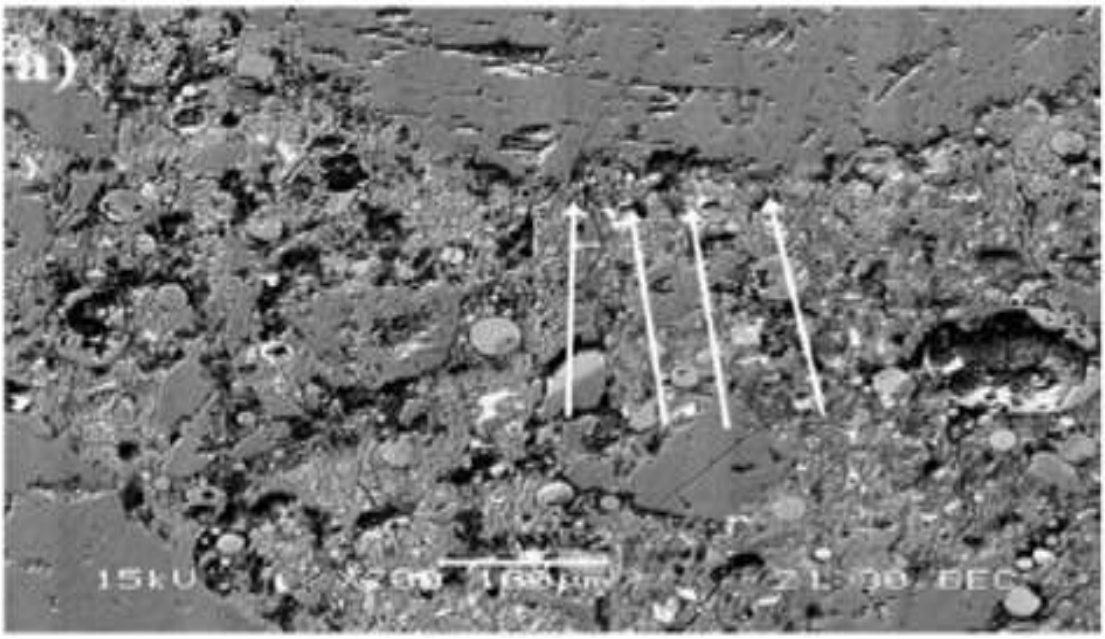


Fig. 2.10.Image from backscattered electron microscopy (BSEM) [53]

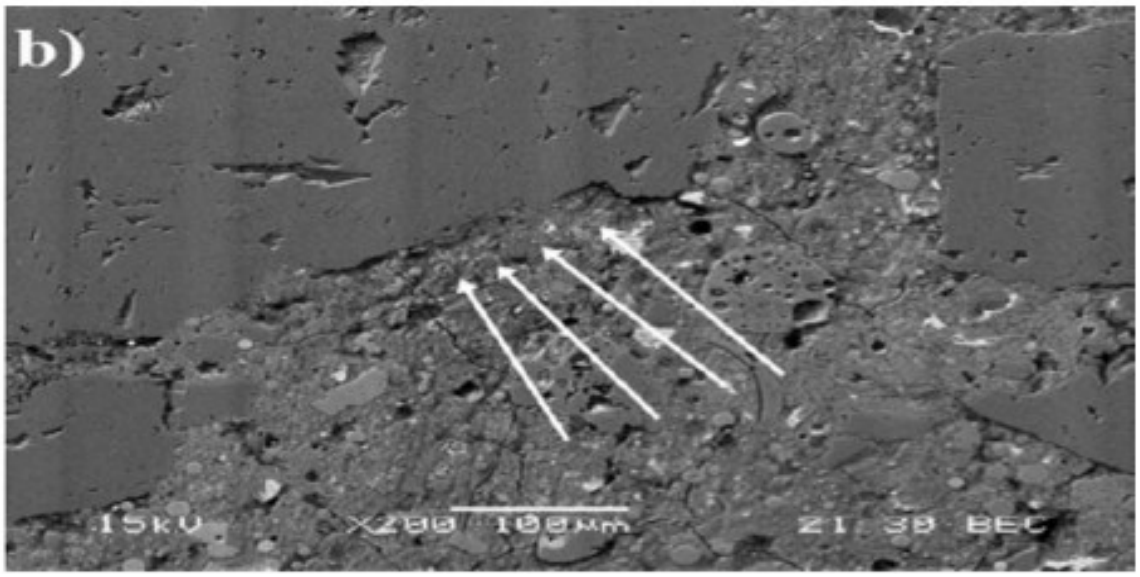
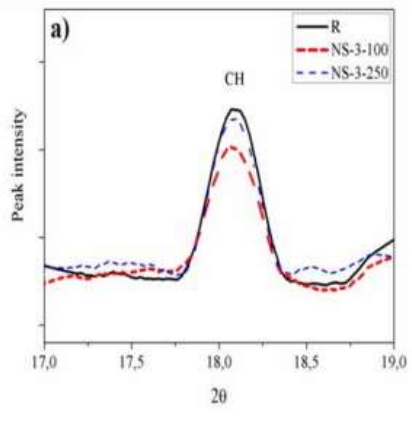


Fig.2.11. Image from backscattered electron microscopy (BSEM) [53]

The authors investigated the effect of nano-SiO2 on the performance of cement concrete by replacing its cement with 3% and 6% of nano-SiO2 by weight. Fly ash of Class F was also in place of cement with 30% by weight. The incorporation of nano-silica together with class F fly ash by 6% and 30% considerably improved the strength of concrete after 28 days. Backscattered scanning electron microscopy (BSEM) analysis exhibited densification in the interfacial transition zone (ITZ) in concrete with nano-SiO2. More hydration has been reported in the concrete with class F fly ash and nano-SiO2 at 28 days relative to the control mix containing only fly ash and the additional dose of nano-SiO2 to minimize the delay in microstructure development and durability improvement of the concrete as shown in Figure 4 and Figure 5 [53].



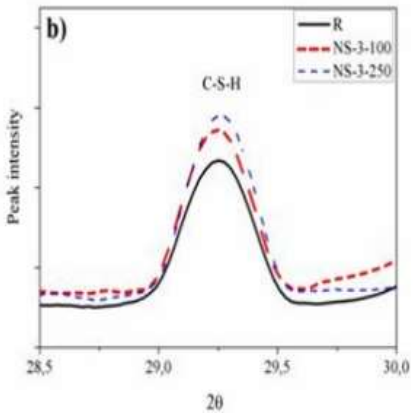


Fig.2.12. XRD pattern of selected mortar [54] *Fig.2.13. XRD pattern of selected mortar [54]*

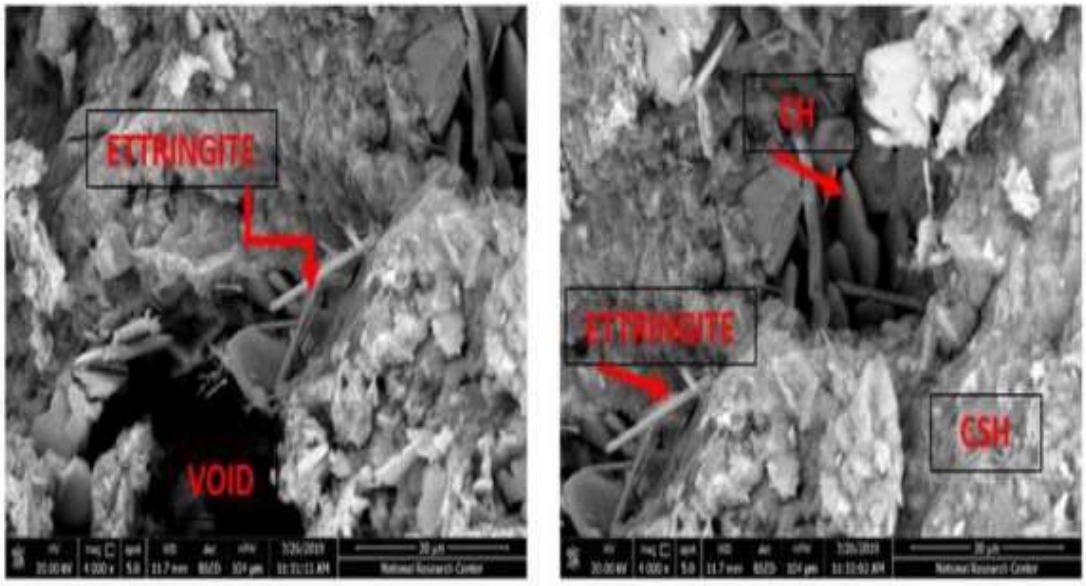


Fig.2.14. SEM image of control mix and nano-silica with cellulose fiber

This paper studied the influence of nano-silica on the performance of polymer cement concrete. Cement was substituted by nano-silica with 1, 3, and 5% by weight. The addition of nano-SiO2 catalyzed the pozzolanic reaction thereby increasing the quantity of C-S-H gel and caused to enhance the mechanical properties of the polymers, and the same was confirmed by XRD analysis. The addition of NS decreased the peak of CH thereby revealing the pozzolanic reaction required by CH to produce more C-S-H shown in Figure 6 and Figure 7 [54].

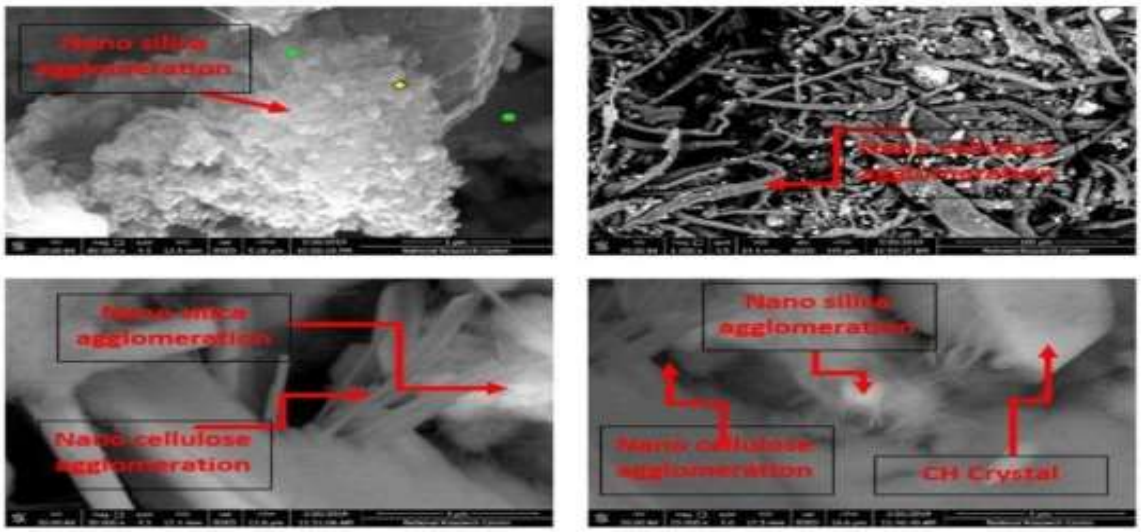


Fig.2.15. SEM image of nano-silica with cellulose fibers [55]

This paper reported the performance of cement composite reinforced with nanocellulose fiber and nano-silica. Cement was replaced by NS with 1, 1.5, 2% by weight. Nano cellulose fibers were added with varying percentages of 0.35, 0.55, and 0.75% by weight. Nano-silica considerably enhanced the crushing, and splitting tensile by 39% and 49% as compared to the control specimen. Higher reinforcement efficiency by modified transition zone between fiber and cementitious matrix under external normal forces had been noticed by SEM analysis. The SEM images are shown in Figures 8 and 9 [55].

This paper investigated the effect of NS as cement replacement on mechanical properties and microstructure of high-performance concrete (HPC) with 1, 2, 3, and 4% by weight. The addition of nano-SiO2 improved the mechanical properties of concrete by reducing the number of pores thereby making the concrete denser at the microstructure level [56].

2.11. Effect of size and type of nano silica and its mixing: -

Hendrix et al. [107] reported that the optimum concentration of nS to achieve the best quality of dispersion in the cementitious environmentwas 2%, and the best dispersion quality was achieved by colloidal nS with 20 nm particle size among the particle sizes ranging from 5 to 75 nm. However, Belkowitz et al. [61] observed that the larger nS particles (46 nm size) with low surface area increased the hydration temperature compared to the smaller nS particles (5 and 16 nm) with higher surface area. It may be due to the high susceptibility of small particles of nS to agglomeration due to their higher surface energy [107]. Esmaeil et al. [58] stated that because of the high surface area of the nS particles and their high reactivity, the lower w/c ratio might also induce uneven dispersion of the nanoparticles and their agglomeration in specific parts of the concrete mix. The colloidal nS with an average particle size of 35 nm exhibited the best efficiency concerning the mechanical and elastic properties of the SCC [88]. When the average particle size of colloidal nS decreased, the strength and elastic modulus decreased as well. The quality of the dispersion nS particles is the most important parameter that influences and controls the characteristics of nS-added concrete [107]. The use of nS as received from the manufacturer can result in an unpredictable effect in the properties of concrete depending on the level of their agglomeration [46]. According to Mohamed [108], wet mixing of nS particles was more effective than mixing them in dry conditions with concrete ingredients to contribute to mechanical properties, attributed to the uniform dispersion of the nanoparticles in the mix. Compared to the mechanical mixing of powdered nS with FA or slag, nS premixed with water, i.e., ultrasonicated nS reduced the dormant period of FA and slag paste. This effect might be ascribed to the agglomeration of fine particles of nS, and subsequent reduction of nucleation sites needed for the formation of hydration products [34]. They also noticed that the cumulative heat produced during the first 24 h in both slag and fly ash cement pastes prepared with ultrasonicated

nS particles was higher than that of nanoparticles mixed mechanically with other constituents, indicating that the sonication of nS and water increased the hydration process. Najigivi et al. [97] obtained a uniform dispersion of nS particles by stirring it with water at a high speed of 120 rpm for 1 min. Elkady et al. [46] reported that 5 min sonication of 1% nS particles before adding into the concrete mix improved the compressive strength by 23% compared to the control sample, so the sonication showed a significant effect on de-agglomeration and better dispersion of nS particles when compared to the other de-agglomeration methods such as homogenization and stirring. As far as the type (powder or colloidal) of nS is concerned, colloidal silica has shown a better effect on concrete compared to its powdered form. Pacheco-Torgal et al. [3] found that the colloidal dispersion of nS was much more effective than the dry powder in controlling CSH degradation caused by the leaching of calcium. Quercia et al. [49] reported that the colloidal nS particles formed a more refined microstructure in SCC due to their high reactivity and pozzolanic action than that by powdered nS. The incorporation of nS into the polycarboxylate-based superplasticizer in HPC resulted in much more efficient dispersion and homogenization during concrete mixing, thereby making the concrete easy to use [28]. According to Li et al. [93], nS has a much higher demand for super plasticizers and cementing efficiency compared to mS.

2.12. The combined effect of nS (Nano-Silica) and mS (Micro-Silica):-

Esmaeili et al. [58] reported that using 3% nS with 15% mS increased the compressive strength by 67.5% compared to the control mix while adding 9% nS alone showed a strength increase of 57.21%. It can be ascribed to the more effective filling effect of the combined nS and mS particles, which considerably decreased the pores within the cement paste. Similarly, Jalal et al. [43] also observed an enhancement in compressive strength in the binary (cement plus nS or cement plus SF) and ternary system (nS plus silica fume plus cement) of concrete, but the highest was observed in the ternary system. According to Li et al. [93] nS has a much higher demand for superplasticizers (SP) and cementing efficiency than mS, and the SP demand for combined nS and mS was not higher than pure cement demand. Combined use of nS and mS in concrete increased the compressive strength and the elastic modulus, which were higher than those by using nS or mS alone. The highest values of compressive strength and elastic modulus were observed in the blend of 1% nS and 5% mS at 0.3 w/c ratios. Nili et al. [109] reported the highest compressive strength in concrete when 1.5% nS was added with 6% mS.Massana et al. [74] also reported that the combined use of nS and mS demonstrated the highest increase of compressive strength in the HPSCC as mentioned earlier under the subheading ‘‘compressive strength” in this article. According to [74], the inclusion of nS and mS in HPSCC contributed to reducing the pores and their critical diameter due to the combined effect of nS, which reduced the pore size, and mS, which reduced the number of pores in the concrete. In the presence of mS, nS showed a high cementing efficiency factor, and this increase in the cementing efficiency

factor of nS in the presence of mS shows the synergistic effect of the combined addition of nS and mS [93]. A significant increase in electrical resistance was also observed in concrete added with nS and mS together compared to the reference one, but the maximum resistance found in the specimen includes 7.5% mS alone.

Chapter 3
Statement of problem

3. Statement of the Problem: -

3.1. What are the research gaps: -

Research on the use of nano-silica in concrete for compressive strength enhancement has made significant progress, but several gaps remain to be addressed. Some of the main research gaps in this area include:

i. Optimal Dosage and Particle Size: -

Determining the optimal dosage and particle size of nano-silica for maximizing compressive strength remains a key research gap. While various studies have investigated different dosages and particle sizes, there is no consensus on the most effective combination for achieving optimal strength gains. Further research is needed to systematically evaluate the effects of varying dosage levels and particle sizes on compressive strength to establish clear guidelines for concrete mix design.

ii. Effect of Nano-Silica: -

Age Strength: While the long-term effects of nano-silica on compressive strength have been studied to some extent, there is a lack of research focusing specifically on early-age strength development. Understanding how nano silica influences the early hydration kinetics and formation of calcium-silicate-hydrate (C-S-H) gel in concrete can provide valuable insights into its potential for accelerating strength gain during the early curing period.

iii. Influence of Curing Conditions: -

The influence of curing conditions on the effectiveness of nano-silica in enhancing compressive strength requires further investigation. Factors such as temperature, humidity, and curing duration can significantly affect the hydration process and subsequent strength development in nano silica-modified concrete. Research focusing on optimizing curing regimes to maximize the benefits of nano silica for compressive strength improvement is needed.

iv. Performance in Different Concrete Mixtures: -

Most studies on nano silica's effect on compressive strength have focused on concrete mixes containing Ordinary Portland Cement (OPC). However, there is a need to investigate its performance in various types of concrete mixtures, including those incorporating supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume. Understanding how nano silica interacts with different cementitious materials and admixtures can provide valuable insights into its applicability in different concrete formulations.

v. Long-Term Durability and Stability: -

While nano-silica has shown promise in enhancing compressive strength, its long-term durability and stability under various environmental conditions remain uncertain. Research is needed to assess the resistance of nano silica-modified concrete to factors such as freeze-thaw cycles, alkali-silica reaction (ASR), and chemical degradation over extended periods. Long-term

durability studies can help validate the sustainability and performance of nano-silica in concrete applications.

Addressing these research gaps can contribute to a deeper understanding of how nano silica influences compressive strength in concrete and facilitates its effective utilization for enhancing concrete performance in practical applications.

3.2. Objective of Research Work: -

1. Incorporation of Nano-Size Silica in different Percentages in Concrete Mix.
2. Characterization of Nano-Silica using different characterization Technique such as XRD, FESEM and FTIR etc.
3. Calculation of Compressive Strength Of Concrete before and after added Nano-Silica Powder.
4. Comparision of the Compressive Strength and Workability of different percentages of Nano-Sillica added Concrete.
5. To observe the Microstructure of the Concrete before and after addition of Nano-silica by Using FESEM Technique.

Chapter 4
Materials and methodology

4. Materials and methodology: -

The primary aim of mix design is to determine the characteristics of materials intended for use in concrete, ensuring that the produced concrete meets the specified properties. Additionally, the mixed design seeks to achieve the desired workability of fresh concrete while ensuring the attainment of minimum strength in the hardened stage. Furthermore, mix design endeavors to produce concrete economically, thus minimizing wastage.

Materials used in mix design: -

i. Characteristic Strength i.e. Grade of concrete= **M25**

ii. Type of cement = PPC

iii. Exposure =Moderate

iv. Workability = Medium

v. Type of cement = R.C.C.

vi. Specific gravity of course aggregate =2.78

vii. Specific gravity of fine aggregate= 2.66

viii. Specific gravity of cement= 2.95

ix. Nano-Silica – White-colored nano-silica was used in this experiment. The spherical particle of Nano-silica was less than 1mm in diameter. The specific gravity of nano-silica was 2.3.

x. water - Clean, Potable water was used in the mix design.

Solution

Target strength of Mix Proportioning: -

According to clause 3.2 of IS 10262:2009

$f'_{ck} = fck+1.65S$

f'_{ck} = Target mean compressive strength at 28 days in N/mm^2

f_{ck} = Characteristic compressive strength at 28 days in N/mm^2

S = Standard Deviation N/mm^2

As per Table-1 of IS 10262:2009

$\mathbf{f'_{ck} = f_{ck} + 1.65S}$

$f'_{ck} = 25 + 1.65 \times 4$

$f'_{ck} = 25 + 6.6$

$\mathbf{f'_{ck} = 31.6 N/mm^2}$

Selection of water cement ratio: -

According to Table 5 of IS 456: 2000 for M25 concrete.

The maximum free water cement ratio = 0.49

Selection of water content: -

As per clause, 4.2 of IS 10262:2009,

The quantity of maximum mixing water per unit volume of concrete may be determined from Table 2. The water content in Table 2, is for angular coarse aggregate and for 25 to 50 mm slump range. The water estimate in Table 2 can be reduced by approximately 10kg per sub angular aggregates approximately 10 kg per sub angular aggregates 20 kg for gravel with some crush's particles and 25 kg for rounded gravel to produce same workability. For the desired workability (other than 25 to 0 mm slump range) the required water cement may be established by trial or as increase by about 3% for every additional 25, slump and alternately by use of chemical admixture conforming to IS 9103

So, From Table 2 IS 10262:2009 Maximum water content per cubic meter of concrete for normal maximum size of aggregate i.e. 20mm is 186 kg. This is corresponding to standard surface dry aggregate.

For medium workability i.e. 75 mm slump (as per IS 456: 2000 clause 7.1)

As per clause 4.2 of IS 10262:2009 increase in water content by 3% for every addition of 25 mm slump (other than 25-50 mm slump)

So, estimated water content for 75 mm slump, 186+ (3/100) *186= 191.58

Calculation of cement content: -

Free water cement ratio = 0.49So, calculated cement content =191.58/0.49= 390.97 km/m^3

From Table 5 of IS 456: 2000

Minimum cement content for M25 concrete at moderate exposure condition = 300 kg/m^3

For 20 mm Nominal Maximum size of aggregate.

As per Table 6 of IS 456: 2000

Adjustment to minimum cement content aggregate other than 20 mm Nominal Maximum size is 30 kg/m^3

So, Net minimum cement content required = (390.97-30) kg/m^3

As 390.97 kg/m^3> 360.97 kg/m^3 hence, Justified.

Proportion for Volume of course aggregate and fine aggregate content: -

As per clause 4.4 of IS 10262:2009, the approximate value for aggregate volume is given in Table 3.

For a water-cement ratio of 0.6, which may be suitably adjusted for the water-cement ratio. It can be seen that for equal workability, the volume of course aggregate in a volume of concrete is dependent only on its nominal maximum site and grading zone of fine aggregate. so, from Table 3 volume of course aggregate corresponding to 20 mm nominal maximum size of aggregate and fine aggregate (zone 2) for water cement ratio of 0.62

In the present case water cement ratio is 0.49.

Therefore volume of course aggregate is required to be decreased to increase the fine aggregate content. As the water-cement ratio is higher than 0.05, The proportion for the volume of course aggregate is decreased by 0.0 (at the rate of – 1+/-0.01 for every +/- 0.05 change in the water-cement ratio)

Therefore, corrected proportion of the volume of aggregate for water cement ratio of 0.49 to 0.62

Volume of course aggregate = 0.62 x unit volume of Total aggregate for zone 2 of fine aggregate

Volume of fine aggregate = 1- 0.62 = 0.38/ unit volume of total aggregate

Mix Calculation: -

The mix calculation per unit volume of concrete shall be as follows-

(a) Volume of concrete = 1 m^3

(b) Volume of cement =

$$\frac{\text{Mass of Concrete}}{Specific\ gravity\ of\ Cement} x \frac{1}{1000} = \frac{390.97}{2.95} x \frac{1}{1000} = 0.132\text{m}^3$$

(C) Volume of water =

$$\frac{Mass\ of\ water}{Specific\ gravity\ of\ water} x \frac{1}{1000} = \frac{191.58}{1} x \frac{1}{1000} = 0.191\ m^3$$

(d) Volume of all aggregate = [a-(b+c)] = [1-(0.132+.191)] = [1-.323] =0.677 m^3

(e) Mass of course aggregate = 0.677x volume of course aggregate x Sp. Gravity of course aggregate x 1000 = 0.677 x 0.62 x 2.78 x 1000 = 1166.87 kg

(f) Mass of fine aggregate = 0.677 x volume of fine aggregate x sp. Gravity of fine aggregate x 1000 =0.677 x 0.388 x 2.66 x 1000 = 684.31 kg

Mix proportion for Trial No. 1

Cement = 390.97 kg/m^3

Water = 191.58 lit/ m^3

Coarse aggregate=1166.87 kg. /m^3

Fine aggregate = 684.31 kg/m^3

w/c ratio = 0.49

so, the weight of the cement, sand, coarse aggregate, nano silica, and water are as following,

C= 5.91 kg

S= 10.5 kg

CA = 17.88 kg

NS = 90 gm

W= 2.94 kg

Characterization Technique Used:-

i. **XRD (X-ray diffraction) –** XRD is a versatile and powerful technique used in various field for analyzing the structural properties of materials and also for calculating the particle size of silica powder. The instrument specifications were Rigaku Ultima III (Jadavpur University, Kolkata). The Value of 2θ was taken from 20-80 degree.

ii. **FTIR (Fourier Transform Infrared Microscopy) –** It is a technique used to analyze the chemical composition of materials. It identifies functional groups by measuring their absorption of infrared radiation, enabling qualitative and quantitative analysis. The instruments Used is Prestige 22, Shimadzu (Jadavpur University, Kolkata). The Optical properties were studied using UV-Vis (V- 630, JASCO).

iii. **FESEM (Field Emission Scanning Electron Microscopy) -** It is a versatile tool for material characterization, offering detailed insights into surface morphology, microstructure, chemical composition, and properties across a wide range of materials and applications. The Model used is FESEM, ZEISS Sigma 300 (Jadavpur University, Kolkata), operated at 10KV.

Chapter 5
Results and discussions

5. Result and discussion: -

5.1. X-ray Diffraction (XRD)Characterization: -

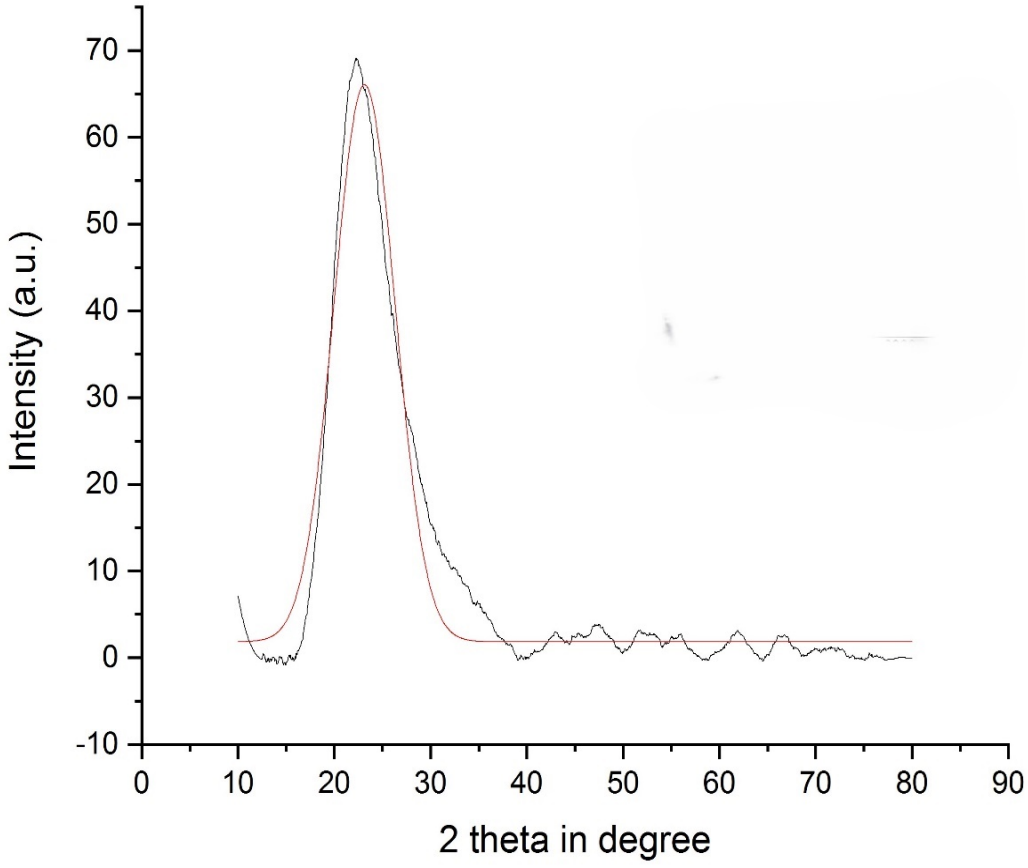


Fig.5.1. XRD of Silica Nano Particles

Fig. 5.1 shows the XRD pattern of silica nano powder. The figure shows a broad peak at 2Θ = 25.4 degree and d = 3.8À, Comparing with JCPDS, this peak represents silica phase. The particle size calculated from Scherrer equation from this peak is 105nm**.**

5.2. Fourier Transform Infrared Spectroscopy(FTIR) Analysis: -

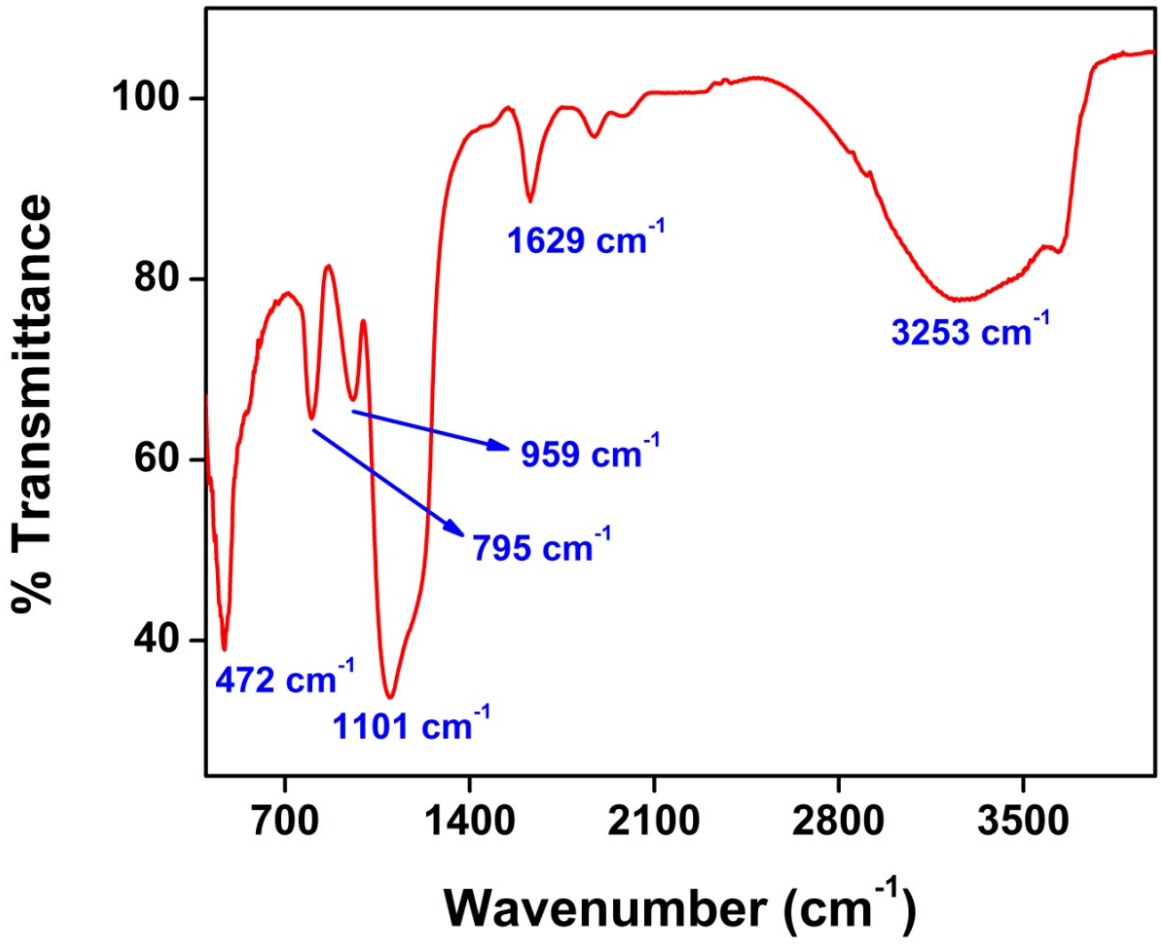


Fig.5.2. FTIR for Silica Nano Particles

Figure 5.2, shows the FTIR peaks of nano-silica observed on around 3253 cm^{-1} and 1629 cm^{-1} are due to stretching and bending vibration of O-H bond of either free –OH group or H2O molecules that are present to a small amount in silica particles. The peaks around 472 and 959 cm^{-1} appeared for out-of-plane bending of the Si-O-Si bond and the Si-O bond's stretching vibration, respectively. The presence of a very broad strong peak around 1101 cm^{-1} can be assigned as the stretching of the C-O bond.

5.3. Scanning Electron Microscope (SEM)Analysis: -

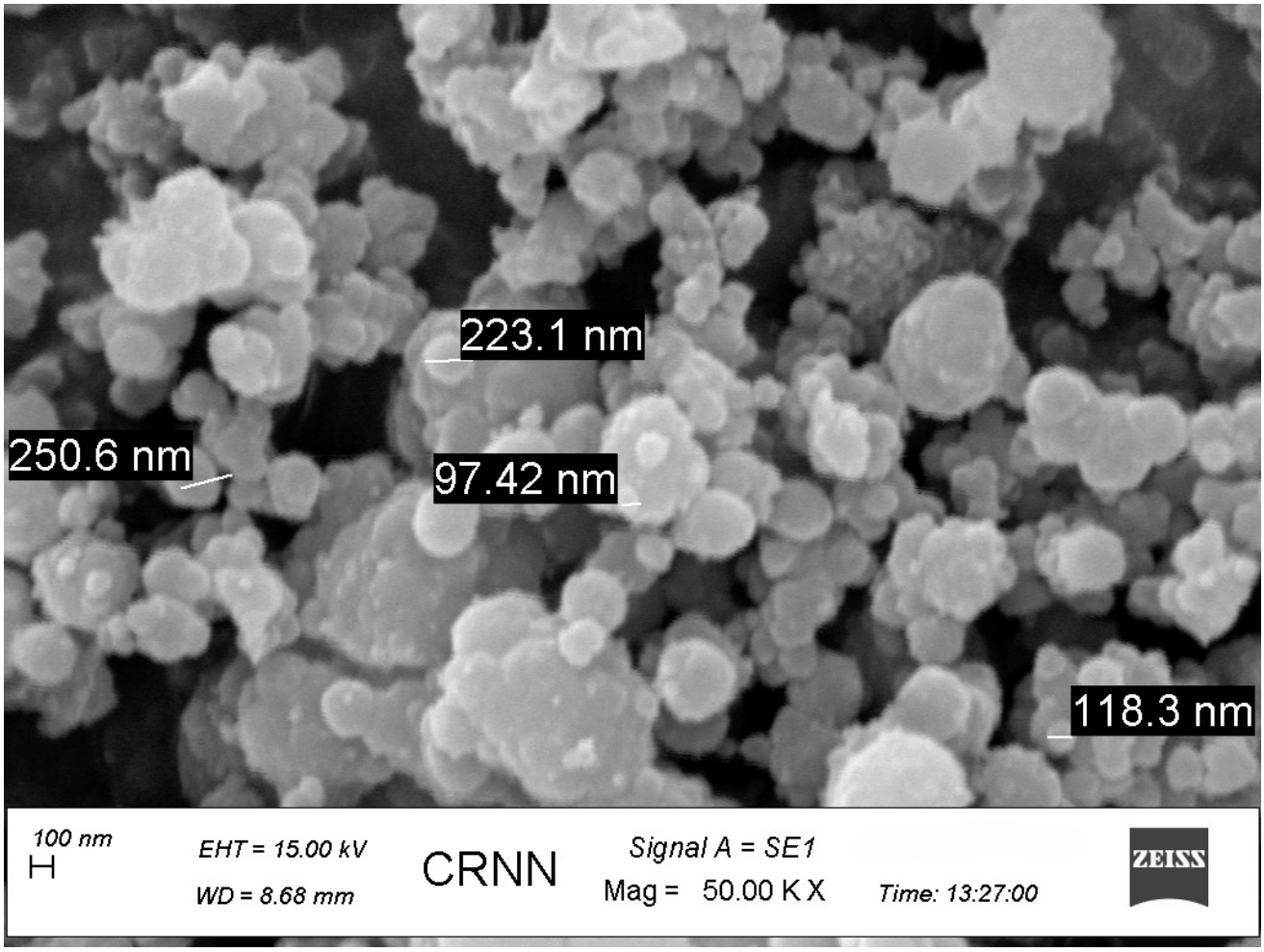


Fig.5.3. SEM Image of Silica Nano Particles

Figure 5.3, shows the Scanning Electron Microscope (SEM) image of silica nanoparticles provides a visual representation of the morphology, size, and distribution of these particles at the nanoscale level. Silica nanoparticles typically exhibit a variety of shapes such as spherical, rod-like, or irregular. The SEM image will depict the actual shape of the nanoparticles, providing insight into their structuralcharacteristics.SEM can provide information about the surface texture and roughness of the nanoparticles. This is important as it can influence properties such as surface area, reactivity, and dispersibility. In Figure 5.3, the particle range is around 100 nm. So, we take around 100 nm particle size nano silica for our experiment.

5.4. FOR M25 CONCRETE

Table 5.1: -

Mix design of concrete without nano-silica.

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN	Stress (N/mm^2)	Avg Stress (N/mm^2)
						7	1 2 3	177.3 177.6 176.8	17.73 17.76 17.68	17.72
0	4.8kg	8.4kg	14.31kg	2.34kg	0	14	1 2 3	207 187.1 205.4	20.7 18.71 20.54	19.98
						28	1 2 3	215.8 214.6 215.5	21.58 21.46 21.55	**21.53**

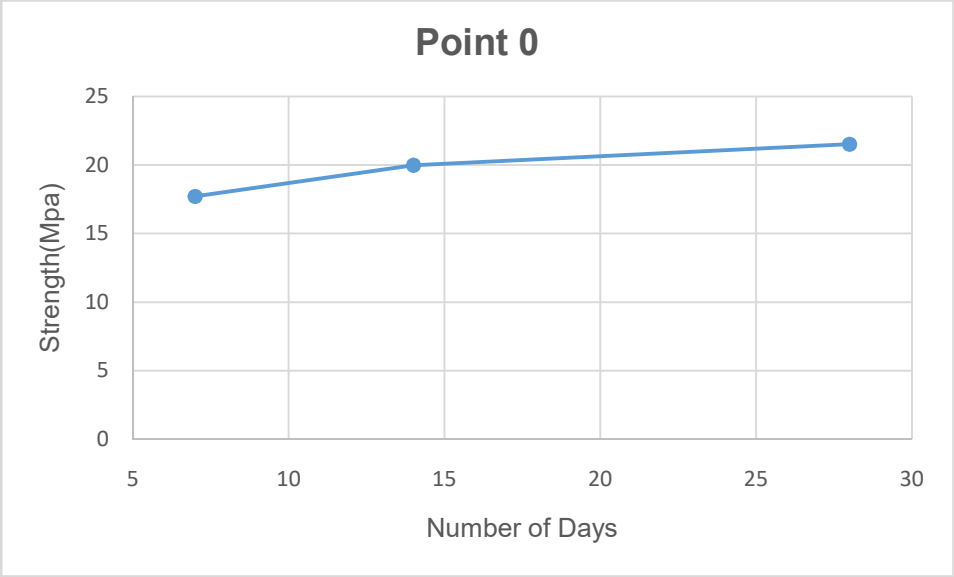


Figure 5.4. Graph of compressive strength without nano-silica concerning days

As per our calculation of the mix design for M25 concrete, the average stress of concrete is 31.6 $N/mm^2$and we get the result almost the same, hence the mix design of concrete calculation is Justified.

Table 5.2: -

Mix design of concrete with nano-silica of 1.5%(90gm).

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN)	Stress (N/mm^2)	Avg Stress (N/mm^2)
						7	1 2 3	215.9 221.6 211.7	21.59 22.16 21.17	21.64
1.5	5.91	10.5 kg	17.88 kg	2.94	90	14	1 2 3	243.3 226.9 218.4	24.33 22.69 21.84	22.92
						28	1 2 3	277.4 255.5 267.9	27.74 25.55 26.79	**26.69**

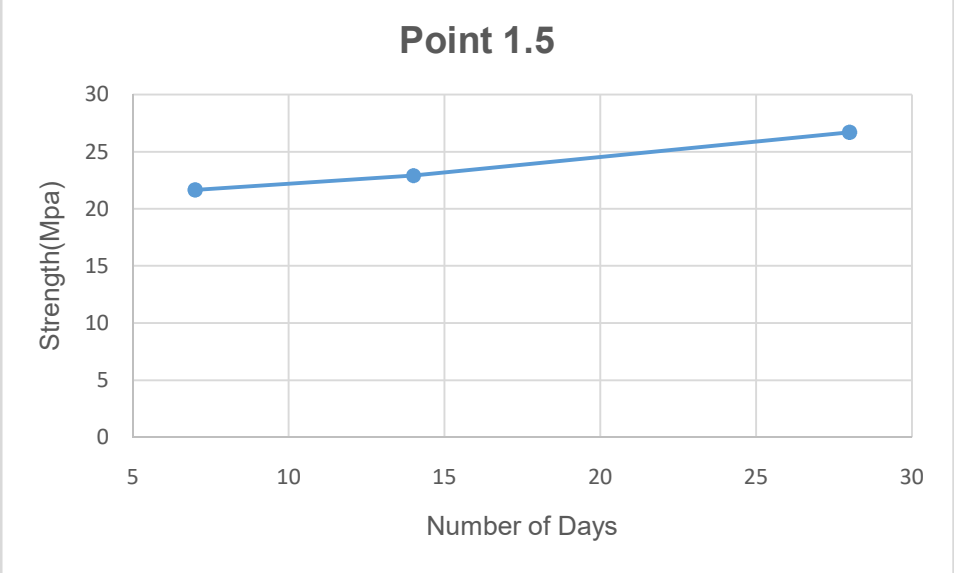


Fig. 5.5. Graph of compressive strength with nano-silica (1.5%) concerning days

Table 5.2 and graph 5.5 of 1.5 % used nano-silica concrete with 5.91kg cement, 10.5 kg sand, 17.88 kg coarse aggregates, and 2.94 kg water, shows the average strength of concrete for 7 days, 14 days and 28 days. And from this table its clear that the strength of 7 days, 14 days and

28 days concrete are much better than the normal concrete. And the strength of 28 days concrete is highest.

Table 5.3: -

Mix design of concrete with nano-silica of 3%(180gm).

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN)	Stress (N/mm^2)	Avg Stress (N/mm^2)
						7	1 2 3	180.7 178.5 175.7	18.07 17.85 17.57	17.83
3	5.82	10.5	17.88	2.94	180	14	1 2 3	196.6 206.7 202.1	19.66 20.67 20.21	20.18
						28	1 2 3	228.8 228.5 194.8	22.88 22.85 19.48	**21.73**

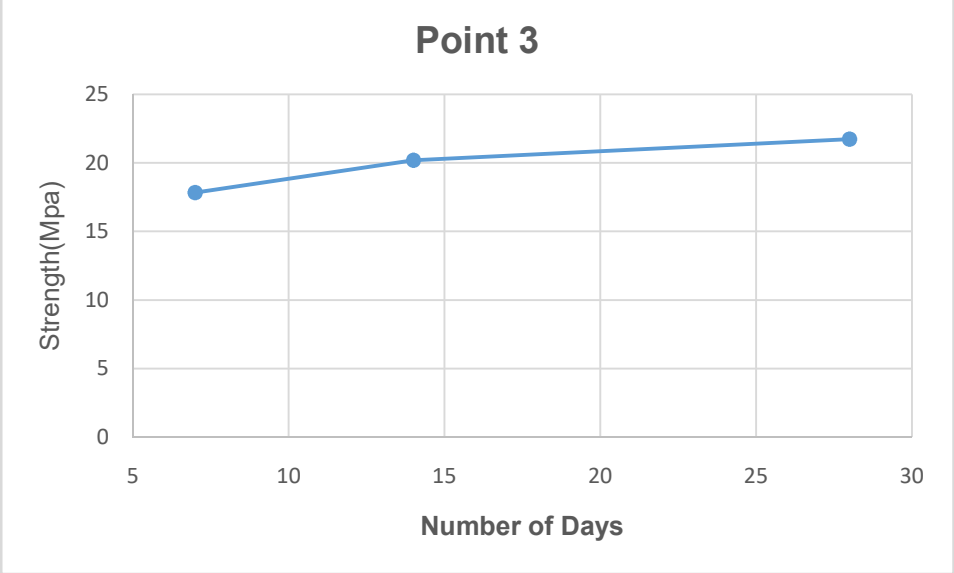


Fig. 5.6. Graph of compressive strength with nano-silica (3%) concerning days

From Table 5.3 and graph 5.6 where 3% nano-silica used concrete with 5.82 kg cement, 10.5 kg sand, 17.88 kg coarse aggregates and 2.94 kg water, that also shows better compressive strength than normal concrete and here also the 28 days concrete shows the most compressive strength. But the compressive strength of 3% nano-silica used concrete cannot bit the compressive strength of 1.5% used nano-silica concrete. So, it is a most important point of this table.

Table5.4: -

Mix design of concrete with nano-silica of 4.5%(270gm).

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN)	Stress (N/mm^2)	Avg Stress (N/mm^2)
						7	1	99.3	9.93	10.89
							2	110.9	11.09	
							3	116.6	11.66	
4.5	5.73	10.5	17.88	2.94	270	14	1	108.2	10.82	10.96
							2	115.2	11.52	
							3	105.5	10.55	
						28	1	259.4	25.94	**26.09**
							2	276.2	27.62	
							3	247.2	24.72	

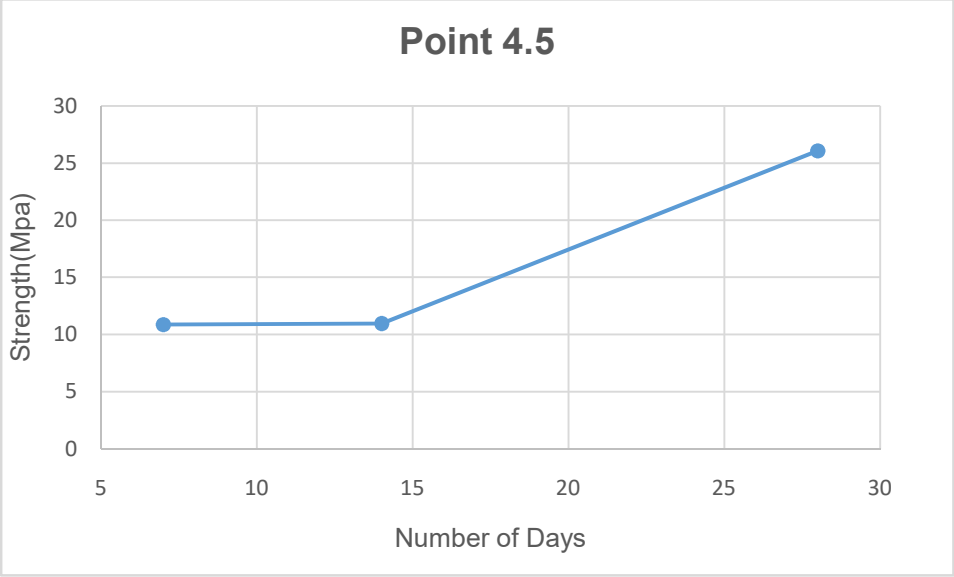


Fig. 5.7. Graph of compressive strength with nano-silica (4.5%) concerning days

Now Table 5.4 and graph 5.7 4.5% used nano-silica concrete with 5.73 kg cement, 10.5 kg sand, 17.88 kg coarse aggregates and 2.94 kg water, shows less compressive strength for 1st two groups like 7 days concrete and 14 days concrete than normal concrete but for 28 days it jumps high and shows more efficiency in strength than normal concrete as well as 1st two groups.

Table 5.5: -

Mix design of concrete with nano-silica of 6%(360gm).

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN)	Stress (N/mm^2)	Avg Stress (N/mm^2)
						7	1 2 3	64.5 60.5 63.1	6.45 6.05 6.31	6.27
6	5.64	10.5	17.88	2.94	360	14	1 2 3	59.8 84.8 100.3	5.98 8.48 10.03	8.16
						28	1 2 3	64.9 82.7 102.7	6.49 8.27 10.27	**8.34**

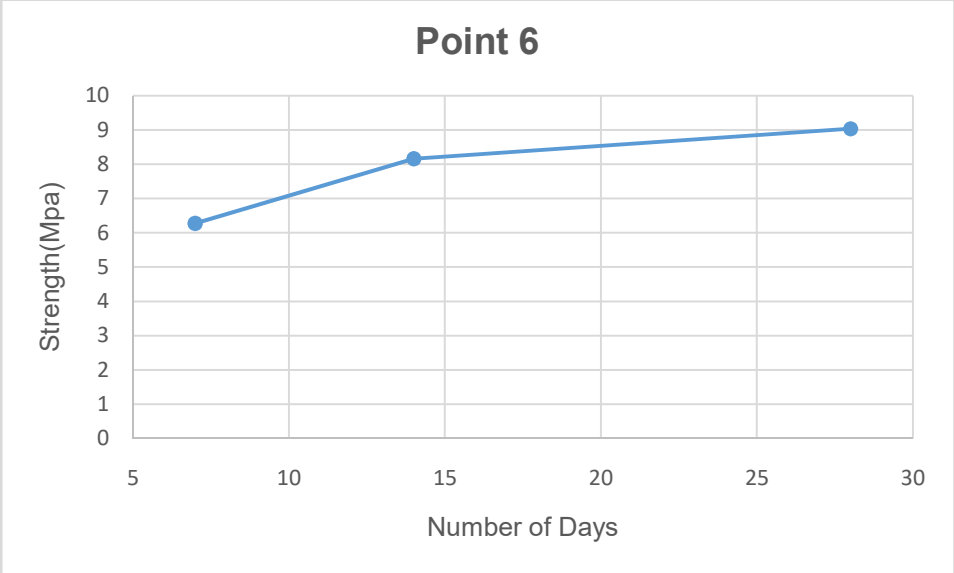


Fig. 5.8. Graph of compressive strength with nano-silica (6%) concerning days

Table 5.5 and graph 5.8 6% used nano-silica concrete with 5.64 kg cement, 10.5 kg sand, 17.88 kg coarse aggregates show very very less strength in 7, 14 a and 2.94 kg water, and 28 days than the normal concrete. Because here the percentages of nano-silica high means percentages of fine particles high and fine particles absorbed more water. But here water is constants as previous percentage. So, when the fine particles absorbed more water then the concrete get less water for binding and shows less workability and less strength.

Table 5.6: -

Comparison of compressive strength of all percentages according to days.

Sr. No.	**Nano-Silica used (%)**	**Compressive Strength (N/mm^2)**		
		7Days	**14Days**	**28Days**
1	0	17.72	19.98	21.53
2	1.5	21.64	22.92	**26.69**
3	3	17.83	20.18	21.73
4	4.5	10.89	10.96	26.09
5	6	6.27	8.16	8.34

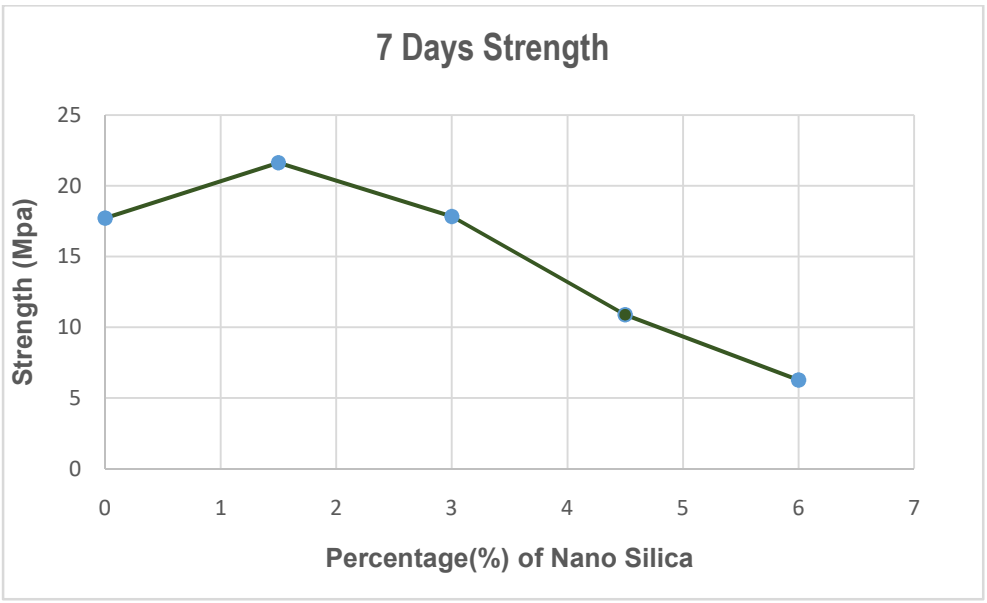


Fig. 5.9. Graph of compressive strength of all percentages for 7 days

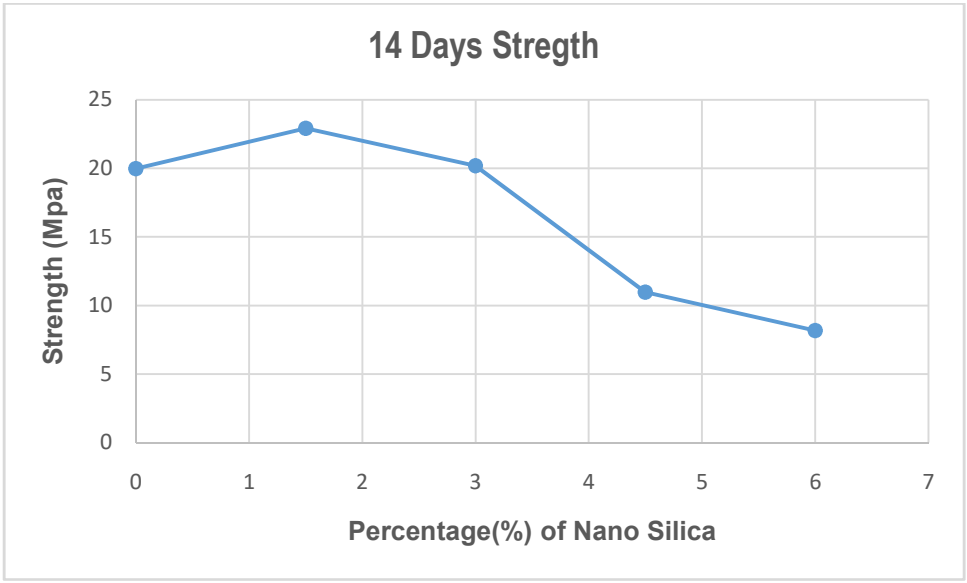


Fig. 5.10. Graph of compressive strength of all percentages for 14 days

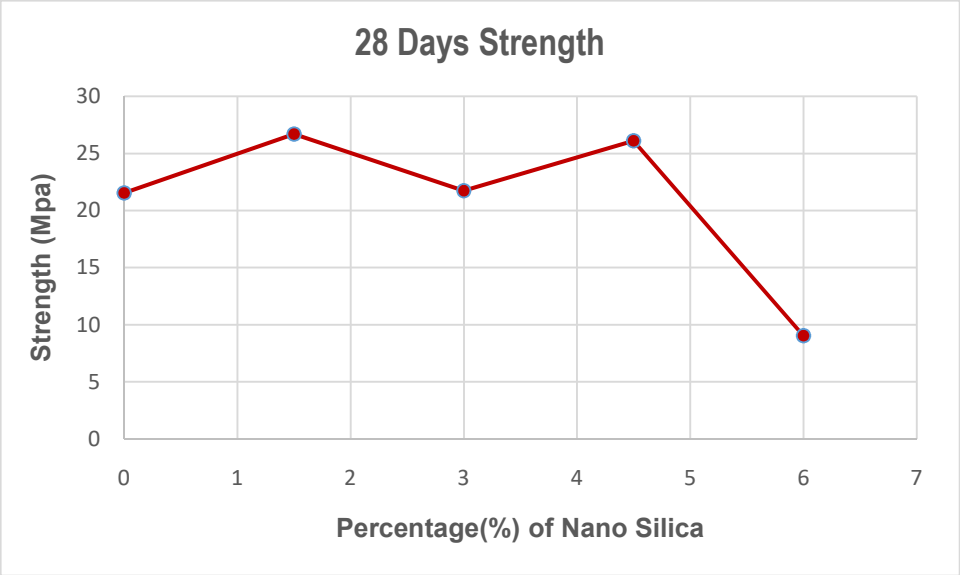


Fig. 5.11. Graph of compressive strength of all percentages for 28 days

From all the tables, calculations, and graphs, we observed that we got the highest compressive strength from 1.5% nano-silica used in concrete in 28 days which is 26.69N/mm2. And from 4.5% the compressive strength started decreasing and in percentage 6 the strength decreased rapidly. So, we may get the highest compressive strength from 1.5% used nano silica within 28 days. We do not need to add more materials and this is a big advantage of this work.

But there are some disadvantages also present. The decrease in compressive strength from 4.5 % occurred due to decreasing in workability. And the workability decreases because the nano-silica has a hydrophilic property in it and the particle size is very fine, and fine particles absorb more water. So, when the water is absorbed more than the concrete faces a lack of water and for that the binding of concrete properly is not possible. Due to this reason, the workability started decreasing and the compressive strength also started decreasing.

After observing this we added extra water with 6% used nano silica mixed concrete and we got more compressive strength than the previous concrete with 6% used nano silica because the workability gaineda little more after adding some water. That's why the compressive strength also increased.

But from all these tables and graphs we can say that the increasing of compressive strength of nano-silica used concrete increased the strength till a fixed percentage after that if we added more nano-silica it does not gives the better strength than the highest strength.

Table 5.7: -

Mix design of concrete with nano-silica of 6%(360gm) with extra water

Point	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Nano Silica (gm)	Days	Serial No	Breaking Point (KN)	Stress (N/mm2)	Avg Stress (N/mm2)
						7	1 2 3	74.5 60.5 63.1	7.45 6.05 6.31	6.60
6	5.64	10.5	17.88	2.94+1.60= 4.54	360	14	1 2 3	59.8 84.8 123.7	5.98 8.48 12.37	**8.94**
						28	1 2 3	64.9 82.7 100.3	6.49 8.27 10.03	8.26

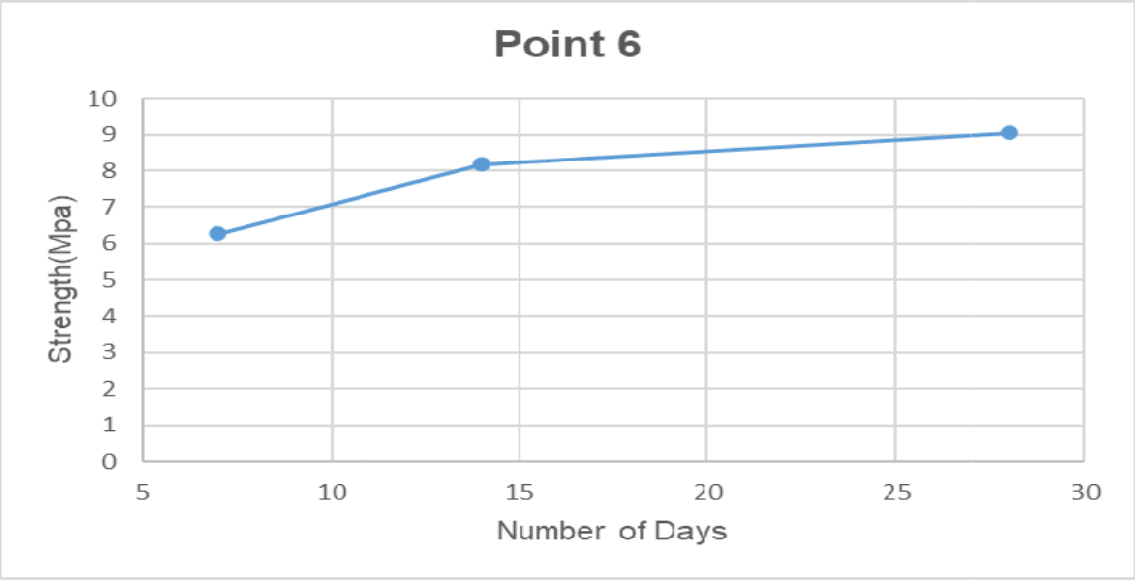


Fig. 5.12. Graph of compressive strength with nano-silica (6%) with extra water concerning days

Here in Table 5.7 and graph 5.12 6% nano-silica used concrete with 5.64 kg cement, 10.5 kg sand, 17.88 kg coarse aggregates and **4.54 kg** water shows little more strength than the previous 6% used nano-silica mixed concrete where the water is **2.94 kg.**

Table 5.8: -

Comparisons the 6% nano silica mixed concrete with constant water and extra water.

Sr.no	Point	Water (kg)	Nano Silica (gm)	7 days strength	14 days strength	28 days strength
1	6	2.94	360	6.27	8.16	8.34
2	6	4.54	360	6.60	8.94	8.26

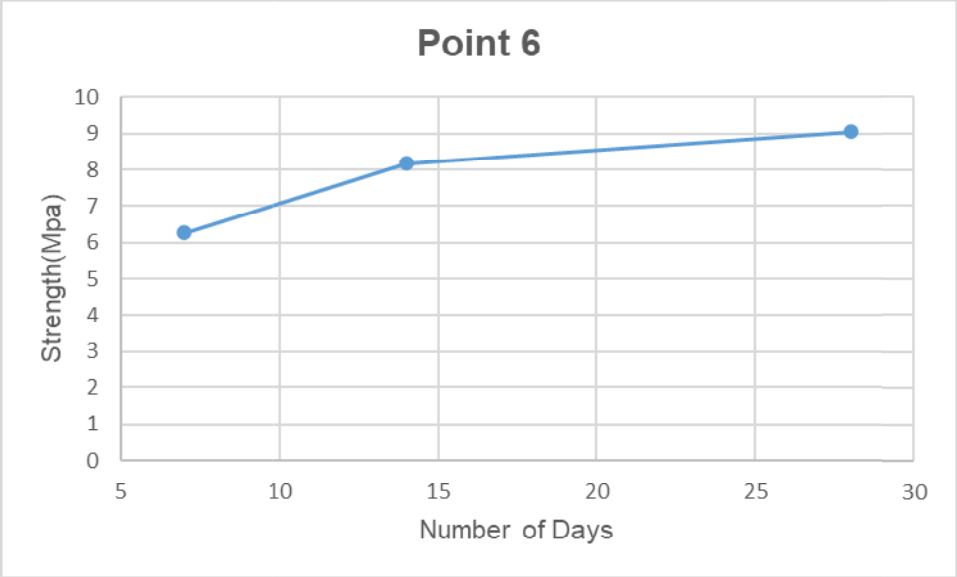


Fig. 5.13. Graph of compressive strength with 6% nano-silica mixed concrete with constant water and extra water concerning days

After this test, we observed that after adding more water the compressive strength little increased but that only for 6% added nano silica mixed concrete. The compressive strength of concrete with 6% nano-silica mixed and extra water that not more than the compressive strength of 1.5% nano-silica mixed concrete, even if it's not more than the other's percentages also.

So, we can concludethat, mixing extra water with any percentages of nano silica mixed concrete, it's cannot give more compressive strength than the highest getting compressive strength. So just

1.5% nano-silicagives us that concrete which has more compressive strength and have others mechanical properties also within 28 days.

5.5. Field Emission Scanning Electron Microscope (FESEM) Analysis for Concrete: -

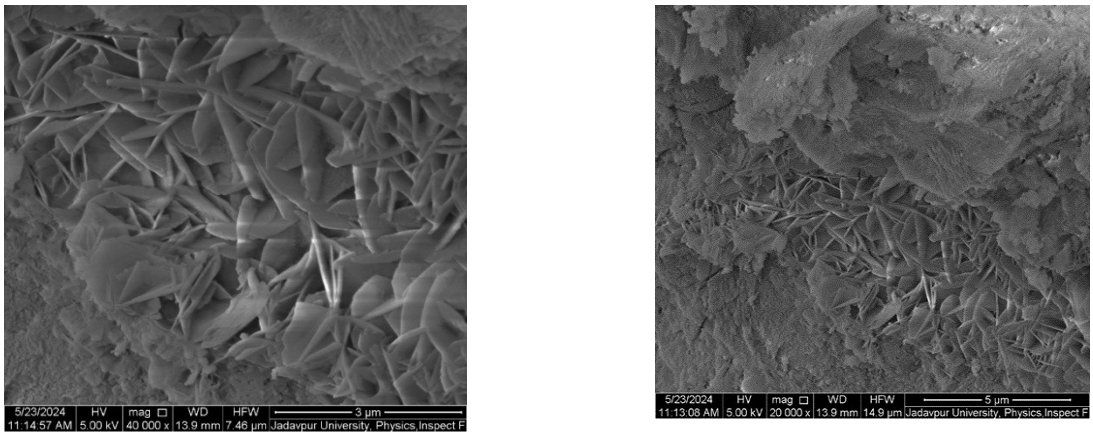


Fig. 5.14. FESEM Image of concrete without Nano silica particles.

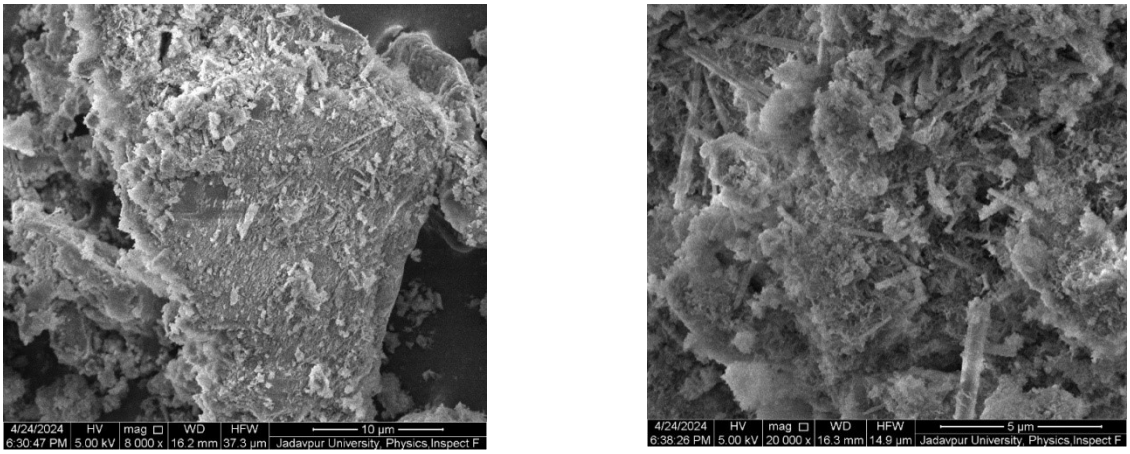


Fig. 5.15. FESEM Image of concrete with Nano silica particles.

From figure 5.14 and 5.15 we can compare the density of concrete. FESEM Images of Without nano-silica concrete have much pores in it but FESEM Images with nano-silica mixed concrete have less pores and more dense structure, because nano-silica have fine particles almost less than 100nm that we see from XRD and SEM analysis of nano-silica , that's why the nano-silica

particles can penetrate deeper into the concrete and fulfilling the voids and for that it shows more dense structure and gives more compressive strength and enhance other mechanical properties than the regular concrete.

Chapter 6
conclusion

6. Conclusion: -

- Nano-silica was incorporated into M25 concrete at varying percentages, demonstrating enhanced compressive strength.
- Characterization Such as XRD, FTIR, and SEM confirmed the phase purity and particle size (105nm) of nano-silica.
- Theoretical compressive strength was calculated for M25 concrete according to IS 10262:2009 Table-1.
- Subsequent calculations determined the quantities of cement, fine aggregates, coarse aggregates, water, and nano-silica for each percentage.
- 45 concrete cubes (100mm) were cast, comprising five percentage groups (0%, 1.5%, 3%, 4.5%, and 6%), with nine cubes for each percentage tested at 7, 14, and 28 days to ascertain average compressive strength.
- Theoretical strength of regular M25 concrete closely matched that of 0% nano-silica concrete.
- Analysis revealed that 1.5% nano-silica admixture yielded the highest compressive strength at 28 days, surpassing regular concrete.
- Compressive strength decreased beyond 3% nano-silica due to reduced workability attributed to water absorption by nano-silica particles.
- Additional water (4.54kg) was introduced in 6% nano-silica concrete, resulting in improved strength compared to the initial mix (2.94kg water), though still inferior to 1.5% nano-silica concrete.
- The findings suggest an optimal percentage for nano-silica inclusion, beyond which diminishing returns and decreased workability occur.
- FESEM analysis of both regular and nano-silica mixed concrete revealed denser structures in the latter, attributed to nano-silica's ability to penetrate and fill voids and pores, thereby enhancing density and mechanical properties.

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A. P. P., Dheeresh Kumar Nayak, B. Sangoju et al. Construction and Building Materials 278 (2021) 122347

18

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