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Synergistic action of nano silica and w/b ratio on accelerated durability performance of concrete

Satish Kumar Chaudhary[1], Ajay Kumar Sinha[2] and Praveen Anand[3]*
Assistant Engineer, Road Construction Department (RCD), Government of Bihar, Bihar, India[1]
Professor, Department of Civil Engineering, National Institute of Technology, Patna, Bihar, India[2]
Research Scholar, Department of Civil Engineering, National Institute of Technology, Patna, Bihar, India[3]

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Abstract

Cement, which is a primary component of concrete and the manufacture of which generates a significant amount of CO2, has an adverse effect on the environment. The environmental effect of manufacturing cement may be decreased by focusing on improving their durability criteria. Sufficient number of nanoparticles may be incorporated to the concrete mix to change the cementitious materials' nano-structure and increase concrete's durability as well. The present article examines the synergistic influence of nano silica (NS) and water-binder (w/b) ratio on concrete subjected to aggressive chemical environment and thus examines the durability of the mix. To study the tendency of binary mix concrete with NS subjected to aggressive environment; acid test, sulphate test and chloride resistance test have been conducted in laboratory. To meet the research objectives the concrete specimen was exposed to 5% sulphuric acid, 5% sodium sulphate and 5% sodium chloride respectively for 60 days. To perform this study, eighteen mix proportion were prepared for M35 concrete by six partial replacement level of cement with NS, viz. 0, 0.5, 1.0, 1.5, 2.0 and 2.5% and three dissimilar w/b ratio, viz. 0.36, 0.40 and 0.44. The percentage drop in weight and compressive strength of concrete specimen after the chemical attack has been measured. The test results showed that there is significant effect of NS and w/b ratio on improving the resistance of concrete towards chemical attack. But the effect of NS inclusion was more prominent than w/b ratio. To gain extra insights for the durability of the mix, flexural tensile test and split tensile strength test was performed. To investigate the morphology and properties of the mix at microscopic level scanning electron microscope (SEM) test was also performed.

Keywords

Nano silica, Acid resistance, Sulphate attack, Chloride resistance, Mix proportion.

1.Introduction

As civil engineering is under constant technological advancements with increasing number of high-rise structures and long-span bridges etc., concrete with greater compressive strength has always been in focus. In certain instances, additional durability features like low water penetrability, resistance to acid, sulphate, and chloride attack, and workability are desirable in addition to compressive strength. Due to its extensive use in constructions, buildings, industries, road bridges, and airport terminals, concrete is one of the most scrutinised materials. Cement plays a significant role among the various materials utilised in the manufacturing of concrete due to its size and adhesiveness.

Concrete without any mineral admixture is not capable to withstand environmental impact. It is vulnerable to the ingress of ions and fluid in extreme environment, due to porous microstructure. In coastal region the ingress of chloride ion in concrete structure through pores lead to corrosion of steel and finally damage of structure [1]. The local environment around the concrete plays a significant role in changing the properties and quality of concrete. In these environments, presence of sulphate either in the ground water or in the soil or in sea water affects the quality of concrete and may prove to be harmful for the underground structures [2, 3]. Concrete infrastructure is susceptible to deterioration due to environmental conditions over time. Common deterioration factors include salt corrosion to reinforced concrete structures, freezing and thawing in cold climates, carbonation from carbon dioxide,

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*Author for correspondence

and chemical attacks from acid solutions. Acid rain contributes to concrete building corrosion. Acid rain is also responsible for degradation of concrete structure constructed in vicinity of industrial area or polluted area by weathering action [4]. The concrete structure, which are constructed in the coastal zone or water retaining structure are more susceptible to aggressive environment. Some common types of chemical attacks which influence the durability of concrete, such as acid attack, sulphate attack, chloride attack and carbonation [5–7]. These drawbacks associated with the cement motivated the need to study advanced mix proportions that would help in increasing the strength as well as the durability of the concrete. To counteract these drawbacks and to produce concrete with improved qualities, several materials known as supplemental cementitious materials (SCMs) are often blended to the concrete mix. Some SCMs include rice husk, fly ash, blast furnace slag, silica fume and nano silica (NS). The SCMs are a waste product, and substituting cement with these materials not only results in high-strength and long-lasting concrete, but is also beneficial for the environment by enhancing sustainability in the construction. Nanoscale research on hydration products (calcium hydroxide, ettringite, mono-sulphate, un hydrated particles, and air spaces) is vital for addressing durability difficulties in concrete and promoting sustainability. Research has been conducted in this area in recent years. Recently, nanotechnology has been employed or proposed for use in a variety of applications, and it has attracted more popularity as a technology for building materials, with both possible benefits and problems highlighted [8–11].

One of the most popular SCMs that is currently being widely used is NS. NS are nanoparticle whose small dosage can significantly improve the concretes properties. With the incorporation of NS along with the micro fibres in the concrete mix, variety of properties on the concrete performance can be investigated. Addition of NS to the concrete is found to be effective in dipping the porosity and also protects the concrete against sulphate attack [12–14]. Researchers found that adding NS improved the compressive and tensile strength of concrete also, particularly in early use. They observed that NS improved cement paste microstructure. It was also concluded that NS concrete resists permeability better [15, 16].

Concrete mixes generated by adding NS as a binder are found to have lower workability as compared to the plain mixes, thus reducing the initial and final setting time [17, 18]. The available literatures also suggests that even small dosage of NS in the concrete mix are effective in increasing the mechanical properties. It is found that by the addition of 4 percentage (by mass of cement) of NS, 70% enhancement in the compressive strength can be achieved [19].

In this research, the main objective was to focus on the effect of NS and water-binder (w/b) ratio on acid, sulphate and chloride resistance of concrete have been studied. Furthermore, flexural strength test, split tensile strength test have been conducted followed by microstructural investigation of the concrete mix by scanning electron microscope (SEM). The impact of w/b and NS on concrete's resistance to acids, sulphates, and chlorides was also investigated.

The article is organised as follows. Literature review is thoroughly discussed in section 2. Experimental sequence, methodology along with material properties are discussed in section 3. Section 4 presents all the results obtained from the experiments conducted. An extensive discussion of the tests is presented in section 5. A separate discussion section including the outcome and limitations of the study is added in section 6. Lastly, the overall conclusion along with the scope for future work is presented in section 7.

2.Literature review

Due to the severe harm that acids add to concrete buildings, acid attacks on hardened concrete have always attracted researchers on improving the acid resistance of the concrete. Due to the expansion of industrial and urban areas, which causes acid media to come into contact with concrete structures, the main reason of acid attacks is the spread of acidic sources [20]. The impact of acid attack on building material has been recognised and studied over centuries. Cement and concrete are negatively impacted by acid precipitation with a pH level in the range of 3.0 to 5.0. Acid attack may be generated from a variety of sources, including silage effluents, acidic waste water, and acidic rain [20–22]. Comparison of biogenic as well as chemical acid attack for evaluating the last stage of corrosion on flexural microstructure of concrete have been addressed [23]. Concrete's alkaline nature makes it extremely susceptible to acidic attack. The acids attack various cement matrix hydration products, resulting in their breakdown and a corresponding decline in the mechanical characteristics of concrete.

Very few of the hydraulic cements, regardless of their kind are able to provide satisfactory and durable resistance to acid attack [24].

Most researchers agree that chloride and sulfate deterioration is the biggest issue for concrete structures, particularly in maritime conditions. Sulphate assault occurs when calcium hydroxide interacts with sulphate ions, converting alumina-containing hydrates to high-sulfate ettringite. When chloride ions contact steel, they de-passivate the surrounding area, causing corrosion in the presence of water/air. Corrosion products are larger than the original steel, causing concrete expansion and spalling. The sulphate attack is a significant threat to the serviceability and durability of concrete. According to some reports, the chemical reactions between sulphates and the hydrated phases of concrete are responsible for causing the sulphate ions to diffuse into the concrete and thus degrade the quality of concrete [25–28]. The preliminary results indicates that sulfur-dioxide contributes significantly in the deterioration of concrete especially in the regions of high pollution. An expanded numerical technique is also available which uses Fick's law and reaction kinetics to estimate concrete deterioration in sodium sulphate solution [29, 30]. The high dilution of chloride and sulphate ions in the marine environment makes it particularly aggressive. Sulphate ions damages the concrete by producing expansive ettringite and gypsum, while chloride ions weaken concrete structures by starting the corrosion of the reinforced steel [31, 32]. One of the most crucial factors that must be to taken into consideration while discussing the durability of concrete is chloride attack. As the facts suggests, chloride attack primarily results in reinforcement corrosion significantly. According to statistics, reinforcing corrosion accounts for more than 40% of structural failures [33]. The leaching of calcium hydroxides and the creation of porosity are two other processes that chloride is known to activate from. Complex reactions are involved in calcium silicate hydrate (CSH). Concrete is negatively impacted by the de-calcification effect of NaCl, the creation of porous CSH, and the leaching of Ca (OH)2 [34, 35]. However, the synergistic impact of mineral admixtures with nanomaterials and their creation process are still unclear. NS has been widely used as a partial substitute for cement and also as a durability modifier for concrete [36]. The synergistic impact of NS and fly ash on hydration process, mechanical property, hardened paste pore size distribution, pozzolanic activity and synergetic effect generation method were explored [37,38]. Research investigated how NS affects the hydration parameters of binary, ternary, and quaternary mixed mortar and cement paste incorporating nano sized admixtures such fly ash and colloidal nano silica (CNS) [39–41]. The NS demonstrates a higher pozzolanic response even at an early stage, which improves water penetration and chloride resistance [42]. From the extensive literature survey conducted, it was found that though the inclusion of NS as SCM significantly improves the properties of concrete and enhances the durability of concrete as well. However, the reports on the optimum dosage of NS along with optimum percentage of w/b ratio is scarce. Also, most of the researches was focused on attempting to analyse single or double parameters affecting the durability of concrete. This motivated the need to make an extensive effort to analyse more parameters to find the importance of varying percentage of NS along with varying the w/b ratio and determine an optimum dosage combination.

3.Materials and methods

3.1Materials

43 Grade ordinary portland cement (OPC), NS, zone III fine aggregate (FA), coarse aggregate (CA) of 20mm gradation, and super plasticizer (Structuro 203) were the constituent materials employed for this investigation (polycarboxylic based). The OPC 43 employed in this investigation, which complies with [43], has a specific gravity (G) of 3.15, a fineness of 0.225m^2/g, and a soundness of 0.8% (Autoclave expansion). The consistency of OPC was noted to be 28% while the initial and final setting time was 60 minutes and 275 minutes respectively. The soundness value and the bulk density of OPC was found to be 2.5mm and 1200kg/m^3 respectively. The NS utilised in the experiment has a regular particle size of 30 to 50 nm and was acquired from the Nano Research Lab in Jamshedpur. *Table 1* displays the chemical make-up of the NS and cement employed in this experiment.

The FA was comprised of sand obtained from the Sone River, and sieve testing showed that it was in zone III of the classification system [44]. As CA, locally accessible crumpled stone "with a maximum graded size of 20 mm has been used." The sieve analysis of a sample of CA verified that it was 20 mm in size, graded according to Indian standards (IS) [44]. *Table 2* and *Table 3* show the physical characteristics of FA and CA respectively.

3.2Mix proportion

Following are the steps used during the mixing process. Firstly, 5 minutes were spent on dry mixing of NS and cementitious ingredients, such as cement. Secondly, the specimens were continuously dry mixed with the addition of aggregates, superplasticizer and sand for 3 minutes to achieve a complete blended mix. Eighteen M35 concrete mixes were made according to IS code [45] using six partial replacements of cement with NS: 0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% by weight of cement and three different w/b ratios: 0.36, 0.40, and 0.44. *Figure 1* presents the samples of the casted specimen. The decrement in water cement ratio to increase the strength reduces workability, however high-rate-water-reducer (HRWR) enables it up to 0.36. Further, IS code [46] restricted the cement content (cementitious material) in a mix up to 450kg/m^3. The mix proportion for M35 concrete with three different w/b ratios has been summarized in *Table 4*. Maximum strength requires proper concrete mixing. First of all, premixing NS powder with half of mixing water and then continues mixing to achieve a uniform dispersion of nano particles then mixing the powder mineral (cement, silica fume) and aggregates for one minute in a drum mixture and adding NS, which was mixed in water, to drum mixture and continue mixing for one minute and finally adding the mixture of remaining half water and super plasticizer to the composition and continue mixing for five minutes to accomplish a fully blended mix.

Figure 1 Casted cube specimens

3.3Methodology

Due to the lack of widely accepted procedures for testing acid, sulphate, and chloride resistance, tests have been carried out in this study based on the results of previous studies and work that has been documented. Cubic concrete specimens of 150 millimetres cubed were casted in the mould so that the impact of chemical assault could be evaluated. Eighteen cubes were casted for each mix type, hence a total of 324 cubes have been casted for this study. After twenty-four hours, the samples were taken out of the mould and allowed to cure in fresh water at normal temperature for twenty-eight days. The cubes were dried for 2–3 hours after curing. Similarly, acid, sulphate, and chloride resistance tests were also performed. To analyse the impact of acid attack on each mix type, the weight of all six surface dry cubes was obtained and the average value was found out, then compressive strength of three cubes was found and the average values was found. Then after the remaining three cubes were submerged in a bucket of 5% sulphuric acid at pH 1.5–2.5 for 60 days. pH was measured in the Laboratory with the help of pH metres. After 60 days, the cubes were removed from solution, dried, and weighed to determine compressive strength. Similarly, the percentage change in weight and compressive strength of cube specimen were found due to sulphate and chloride attack for each mix type.

To conduct flexural strength test, prism specimens of dimension 100mm×100mm×500mm prepared for split tensile strength were tested in lab at a curing age of 28 days. The variation in flexural strength with change in percentage NS content and w/b ratio is discussed in the result section. To conduct split tensile strength, every variation of percentage nano-silica content, cylindrical specimen of diameter 150mm and height 300mm were casted and subjected to testing after 28 days of water curing.

Table 1 Chemical structure of OPC 43 and NS

Type of sample	% (By mass)							
	K_2O+Na_2O	SiO_2	SO_3	Al_2O_3	Fe_2O_3	CaO	MgO	Ignition loss
OPC	1.09	22.11	3.46	5.2	3.45	64.34	2.61	1.45
NS	-	95	-	0.02	0.05	0.08	0.1	2.34

Table 2 Physical property of FA

Parameters	Fineness modulus (FM)	G	Water absorption
Value	2.49	2.66	1.36%

Table 3 Physical property of CA

Parameters	**Impact value**	**Crushing value**	**Specific gravity(G)**	**Water absorption**
Value	29%	24%	2.72	0.76%

Table 4 Mix ratio of M35 concrete

Mix	**%NS**	**w/b**	**Cement(Kg)**	**NS(Kg)**	**HRWR(Kg)**	**Water(Kg)**	**FA(Kg)**	**CA(Kg)**
L_A	0.0	-	425	0	5.1	153	750.38	1156.74
L_B	0.5	-	422.87	2.13	5.1	153	750.38	1156.74
L_C	1.0	-	420.75	4.25	5.1	153	750.38	1156.74
L_D	1.5	0.36	418.62	6.38	5.1	153	750.38	1156.74
L_E	2.0	-	416.50	8.50	5.1	153	750.38	1156.74
L_F	2.5	-	414.37	10.63	5.1	153	750.38	1156.74
I_A	0.0	-	412.50	0	3.3	165	757.05	1132.59
I_B	0.5	-	410.44	2.06	3.3	165	757.05	1132.59
I_C	1.0	-	408.38	4.12	3.3	165	757.05	1132.59
I_D	1.5	0.40	406.31	6.19	3.3	165	757.05	1132.59
I_E	2.0	-	404.25	8.25	3.3	165	757.05	1132.59
I_F	2.5	-	402.19	10.31	3.3	165	757.05	1132.59
H_A	0.0	-	382	0	2.29	168	779.05	1131.31
H_B	0.5	-	380.09	1.91	2.29	168	779.05	1131.31
H_C	1.0	-	378.18	3.82	2.29	168	779.05	1131.31
H_D	1.5	0.44	376.27	5.73	2.29	168	779.05	1131.31
H_E	2.0	-	374.36	7.64	2.29	168	779.05	1131.31
H_F	2.5	-	372.45	9.55	2.29	168	779.05	1131.31

4.Results

This section presents the findings from the experimental program after testing the concrete specimens. A comparative study was carried out for the varying percentage of NS and change in w/b ratio on properties of concrete. Percentage decrease in weight and compressive strength of the samples after the acid, sulphate and chloride attack has been summarized in *Table 5*. The result of flexural strength tests and average split tensile strength for all mixes has been presented in *Table 6*. *Figure 2* and *Figure 3* shows the cube specimen sample after acid and chloride attack respectively.

Figure 1 Cube specimens after acid attack

Figure 2 Cube specimens after sulphate attack

Table 5 Percentage change in weight and strength of specimen made of different mixes

Mix	**Acid attack**		**Sulphate attack**		**Chloride attack**	
	% wt. loss	**% strength loss**	**% wt. loss**	**% strength loss**	**% wt. loss**	**% strength loss**
L_A	8.76	19.52	6.62	15.86	4.25	10.16
L_B	7.92	15.88	5.81	11.89	3.93	8.12
L_C	6.47	12.32	4.75	8.37	3.44	6.65
L_D	5.42	9.56	3.96	7.51	3.05	5.54
L_E	4.51	8.78	3.74	7.38	2.94	5.38
L_F	4.32	8.64	3.62	7.26	2.86	5.25

Mix	Acid attack		Sulphate attack		Chloride attack	
	% wt. loss	% strength loss	% wt. loss	% strength loss	% wt. loss	% strength loss
I_A	8.82	19.88	6.73	16.25	4.37	10.38
I_B	7.95	16.05	5.92	12.05	4.05	8.27
I_C	6.58	12.51	4.81	8.48	3.51	7.06
I_D	5.45	9.64	4.05	7.62	3.16	5.82
I_E	4.63	8.91	3.82	7.52	3.04	5.65
I_F	4.46	8.72	3.73	7.35	2.95	5.48
H_A	8.9	20.12	6.81	16.41	4.45	10.52
H_B	8.05	16.31	6.05	12.21	4.13	8.41
H_C	6.65	12.64	4.89	8.59	3.62	7.16
H_D	5.51	9.85	4.13	7.81	3.25	6.04
H_E	4.58	9.05	3.91	7.72	3.16	5.74
H_F	4.53	8.97	3.84	7.57	3.07	5.66

Table 6 result of flexural strength tests and average split tensile strength for all mixes

Mix	Flexural Strength	% Increase in flexural strength	Split tensile strength	% Increase in split tensile strength
L_A	5.21	0	3.31	0
L_B	5.74	10.28	3.48	5.14
L_C	6.39	22.61	4.11	24.17
L_D	6.85	31.45	4.42	33.53
L_E	6.94	33.28	4.53	36.86
L_F	7.06	33.57	4.62	39.58
I_A	5.1	0	3.27	0
I_B	5.57	9.14	3.39	3.67
I_C	6.15	20.68	3.95	20.79
I_D	6.78	32.88	4.35	33.03
I_E	6.89	35.21	4.42	35.17
I_F	6.94	36.16	4.59	40.37
H_A	4.95	0	3.19	0
H_B	5.5	11.21	3.38	5.96
H_C	6	21.33	3.76	17.87
H_D	6.48	30.96	4.05	26.96
H_E	6.66	34.64	4.21	31.97
H_F	6.69	35.18	4.36	36.68

5.Discussion

This section discusses the experimental results in detail. The investigation undertaken to analyze the durability of the concrete mix was followed by a sequence of experiments whose results has been discussed.

5.1Acid resistance test result

Figure 4 illustrates the % weight loss of cube samples exposed to acid attack and having varied amounts of NS and w/b ratio. The variance in percentage weight loss demonstrates that as the amount of NS grows, weight loss decreases, also, for the same amount of NS, as the w/b ratio rises, the percentage weight loss rises. It is evident from the results that the control mix's percentage weight loss is the highest compared to all other mixes, and that as the amount of NS rises, the percentage weight loss declines. The large specific surface area of NS, which leads to enhanced pozzolanic activity and because of its size in nanometers; it works as filler that makes concrete denser, is responsible for the concrete's good resistance to acid attack.

Figure 5 provides a visual representation of the proportion of cube specimens that had a reduction in strength as a result of acid assault. These specimens had varied percentages of NS and w/b ratios. The graph demonstrates that a rise in the percentage of NS results in a decrease in the percentage of strength loss, whereas an increase in the w/b ratio results in substantial increase in the percentage strength loss. The pozzolanic nature of NS concrete may be responsible for its superior performance against acid attack.

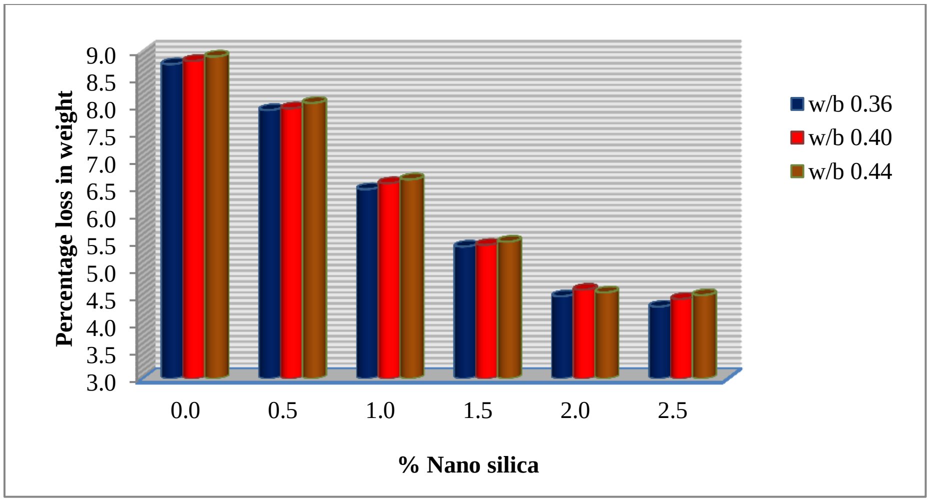


Figure 4 % Loss in weight with varying % of NS and w/b ratio due to acid attack

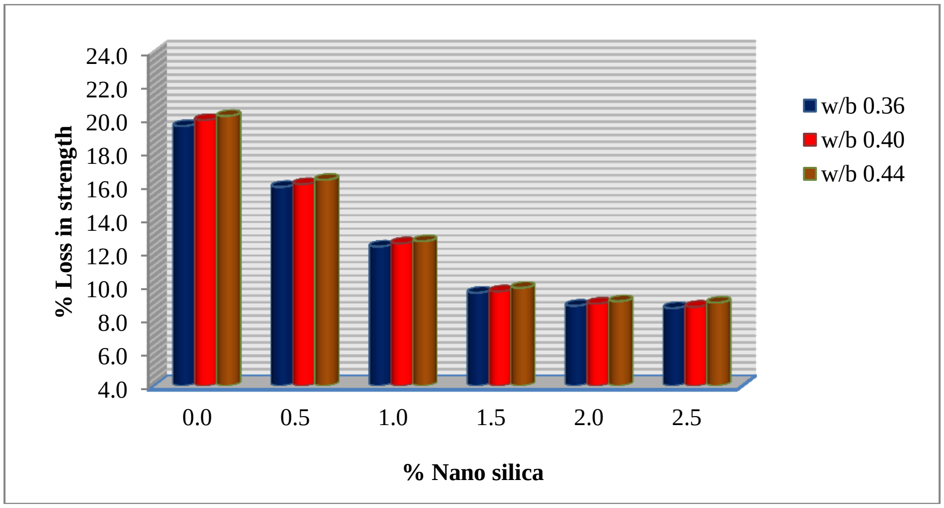


Figure 5 Loss in strength with varying % of NS and w/b ratio due to acid attack

5.2Sulphate resistance test result

Figure 6 presents a visual representation of the proportion of weight loss that occurs as a result of sulphate attack on cube specimens with varying percentage of NS. The variance in percentage weight loss demonstrates that the amount of weight lost decreases as the percentage of NS in the mixture rises, but the amount of weight lost increases for the same percentage of NS when the weight-to-volume ratio is increased. The findings indicate that the control mix suffers the biggest percentage of weight loss when compared to the other mixes, and that this percentage of weight loss reduces as the proportion of NS in the mix increases. Due of its high pozzolanic nature, NS associates with these calcium hydroxide crystals to generate CSH gel, which is why concrete containing NS exhibits good resistance to sulphate attack. The $Ca(OH)_2$ crystal shrinks in size and quantity, and the C-S-H gel fills in the spaces to increase the density of the interfacial transition zone. In *Figure 7*, a graphic representation of the percentage loss in strength caused by sulphate attack on cube specimens with varied percentages of NS and w/b ratio is displayed. The graph indicates that the amount of strength loss experienced for a certain percentage of NS drops as the w/b ratio increases, but the amount of strength loss experienced for the same amount of NS surges when the w/b ratio increases. As can be seen from the results, the percentage strength loss is lowest for the control mix as compared to the other mixes, and it grows as the percentage of NS does. The better performance of NS concrete against sulphate attack may be attributed to the higher consumption of $Ca(OH)_2$ due to the additional pozzolanic reaction by the NS at early age.

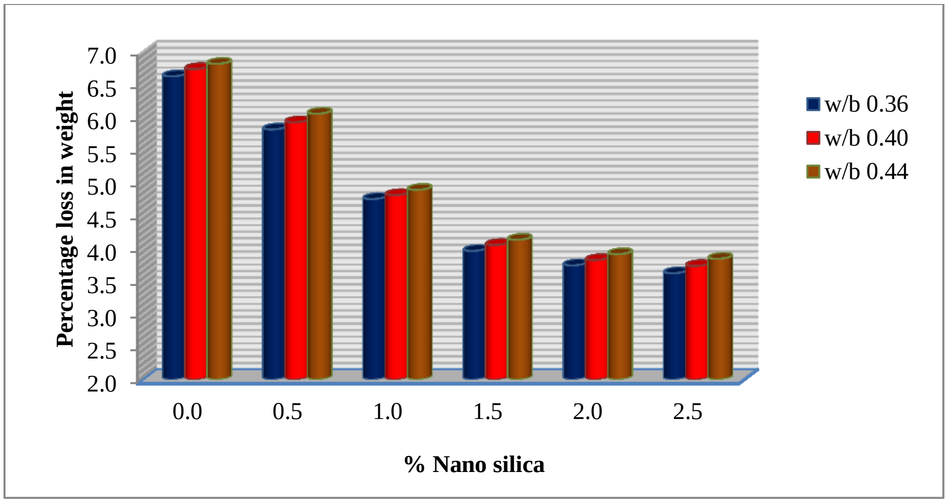


Figure 6 % Loss in weight with varying % of NS and w/b ratio due to sulphate attack

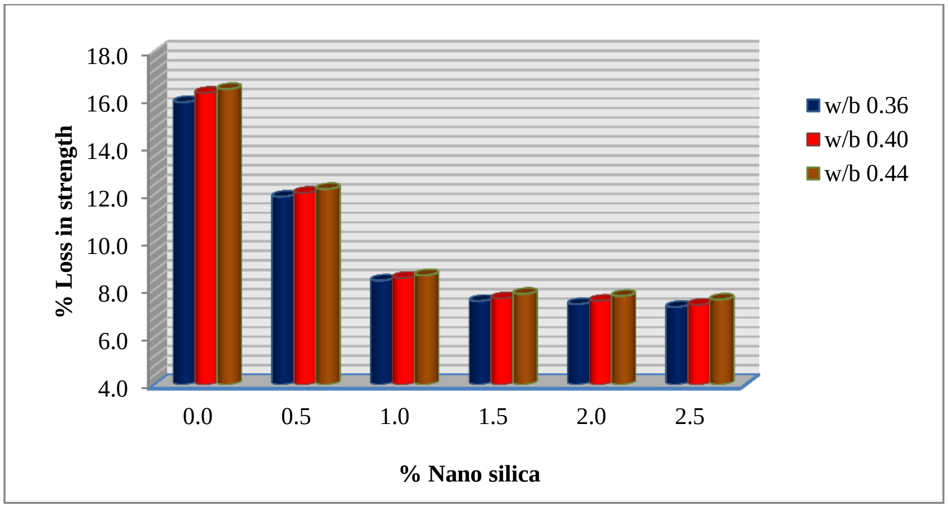


Figure 7 % Loss in strength with varying % of NS and w/b ratio due to sulphate attack

5.3Chloride resistance test result

In *Figure 8*, a graphical representation of the proportion of weight loss that may be attributed to chloride attack on cube specimens with varied percentages of NS and w/b ratios has been shown. The fluctuation in the % weight loss reveals that as the quantity of NS increases, the weight loss lowers; conversely, for the same amount of NS, as the ratio of w/b rises, the percentage weight loss rises. This is shown by the fact that the weight loss decreases. The findings indicate that the control mix suffers the biggest percentage of weight loss when compared to the other mixes, and that this percentage of weight loss reduces as the proportion of NS in the mix increases. NS enhanced concrete demonstrates strong resistance to the corrosive effects of chloride, it can be attributed to the presence of reactive silica, which combines with $Ca(OH)_2$ (a byproduct of cement hydration) in finely divided form and resulting in leaching of $Ca(OH)_2$ and converting them into CSH gel, due to which there are fewer bleed channels and permeability reduced. So, the entrance of anions is minimal. *Figure 9* illustrates the percentage strength loss caused by chloride attack on cube specimens with various amounts of NS and w/b ratio. The graph demonstrates that for a certain percentage of NS, strength loss decreases as the w/b ratio rises, while for the same amount of NS, strength loss increases as the w/b ratio rises. As can be seen from the results, the percentage strength loss is lowest for the control mix with respect to the other mixes, and it grows as the proportion of NS does. The better performance of NS concrete against chloride attack may be attributed to its pozzolanic character, due to which it combines with free lime and increasing structural strength over time.

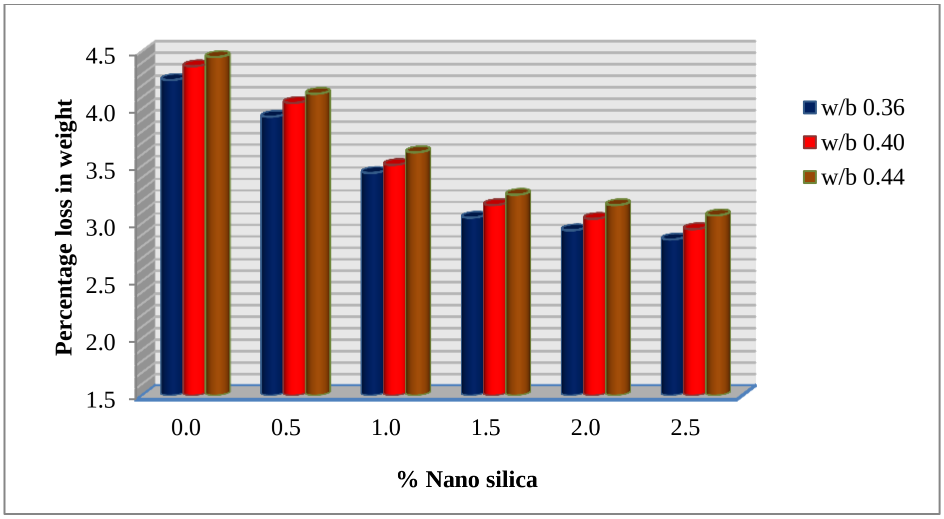


Figure 8 % Loss in weight with varying % of NS and w/b ratio due to chloride attack

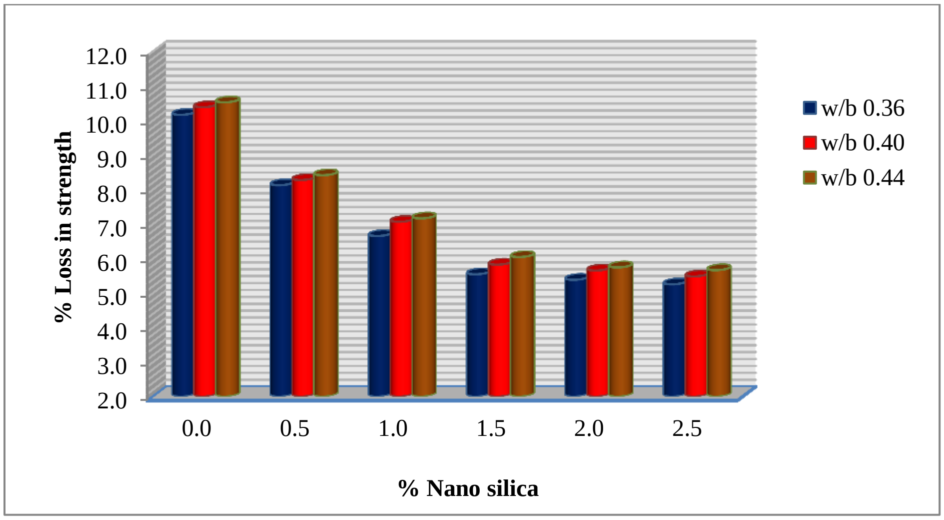


Figure 9 % Loss in strength with varying % of NS and w/b ratio due to chloride attack

5.4Flexural strength test results

Figure 10 shows the variation in flexural strength with change in percentage NS content and w/b ratio. *Figure 11* shows the percentage increase in flexural strength as compare to control mix for different w/b ratio with varying percentage of NS at 28 days. It is evident that all of the concrete specimens containing nanoparticles exhibited flexural strengths greater than those of the control specimens, which may be attributed to the pozzolanic reaction and filler effects of NS. The graph demonstrates that flexural strength values rose with increasing % of NS content. The main effect plots for the 28 days flexural strength have been shown in *Figure 12.*

5.5Split tensile strength test results

Figure 13 shows the variation in split tensile strength with change in percentage NS content and w/b ratio. *Figure 14* shows the percentage increase in split tensile strength as compare to control mix for different w/b ratio with varying percentage of NS at 28 days. The graph shows that as percentage of NS increases, the split tensile strength also shows increasing trend. The main effect plots for the 28 days split tensile strength have been shown in *Figure 15*. The increased binding property of finely divided NS as a result of strong pozzolanic reaction and cement paste aggregate interfacial refinement resulting to better bond strength is the source of the higher split tensile strength for mixes containing NS.

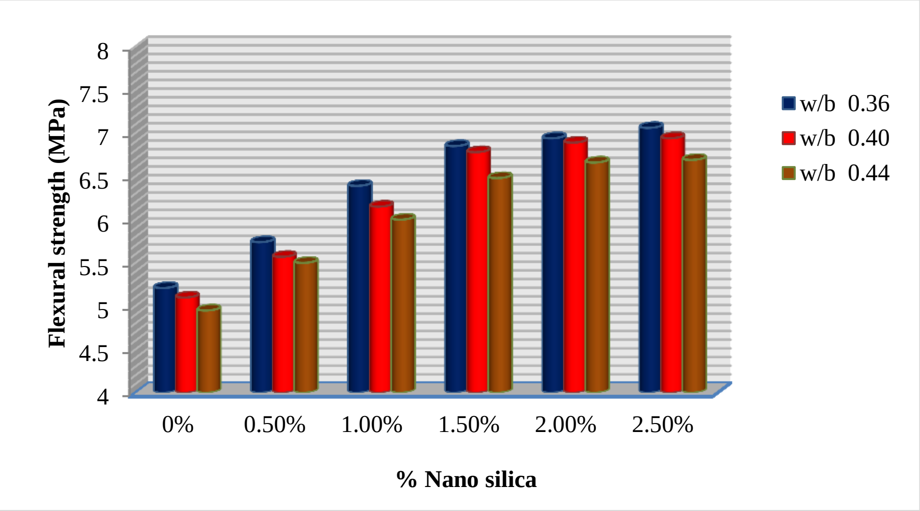


Figure 10 Effect of % NS and w/b ratio on flexural strength

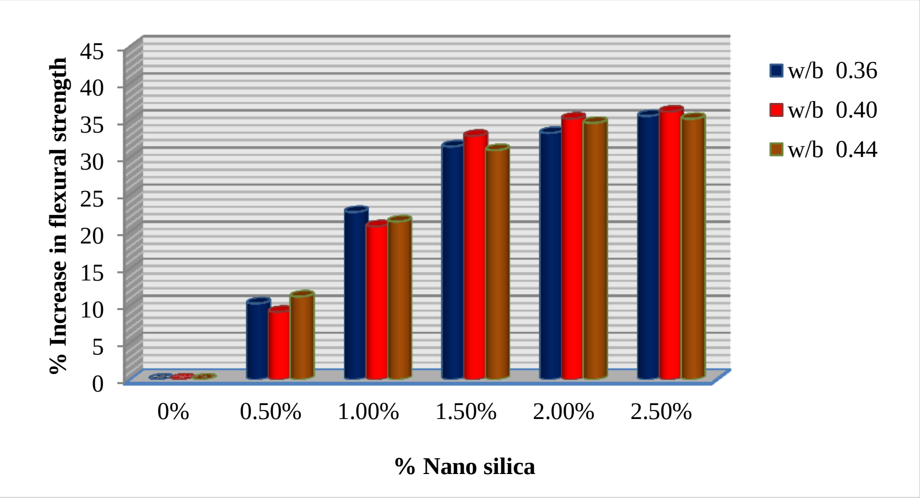


Figure 11 Increase in flexural strength as compare to control mix

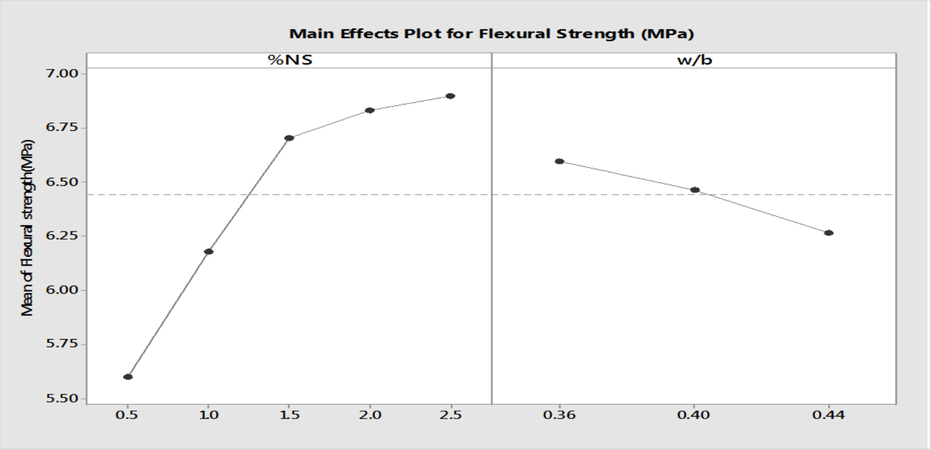


Figure 12 Main effect plot for the 28 days flexural strength

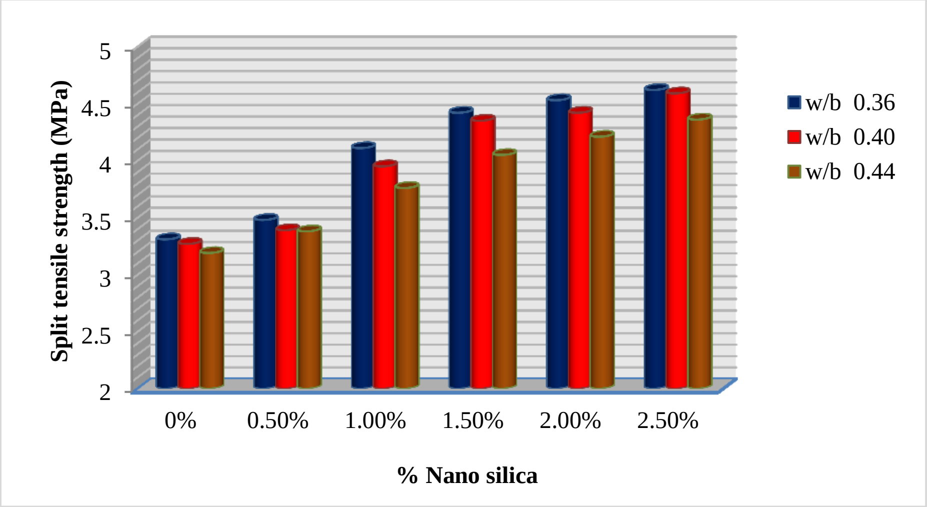


Figure 13 Effect of % NS and w/b ratio on split tensile strength

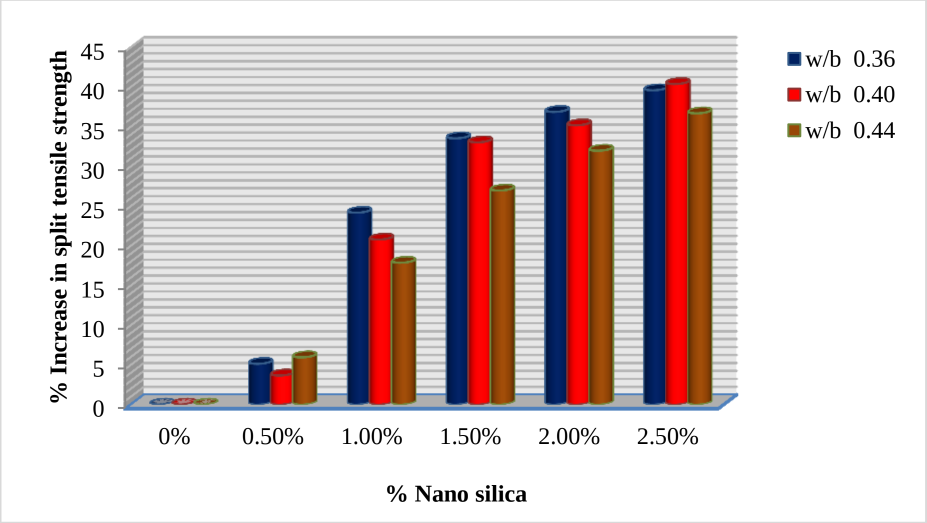


Figure 14 Increase in split-tensile strength as compare to control mix

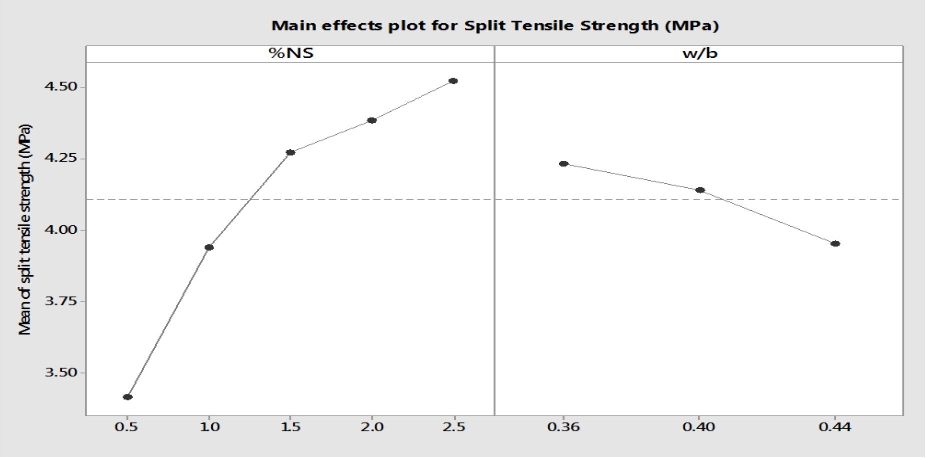
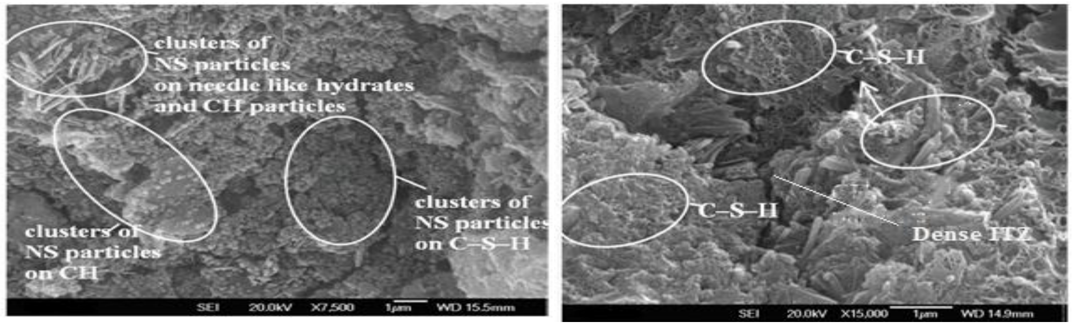


Figure 15 Main effect plots for the 28 days split tensile strength

5.6Results of the SEM test

Figure 16 shows the SEM image of Mix having Binary blending with NS at 7 days of curing. The SEM image shows condensed microstructure and a good dispersion of NS cluster throughout the entire surface of hydrated cement products. Due to high pozzolanic nature of NS, it reacts with portlandite crystals and start converting them into C-S-H gel at early age. NS particles have a higher specific surface area, which provides high chemical reactivity and these particles behaving as a nucleation centers, consequences in early hydration of cementitious materials. These observations are well in accordance with the enhanced mechanical strength result obtained at 7 days. *Figure 15* shows the SEM image of mix having binary blending with NS at 28 days of curing. It can be detected that the most of cluster of NS particle, which was found at 7 days curing period reacts with CSH crystals and convert them into C-S-H gel, due to which a dense and compacted microstructure has been observed at 28 days of curing. The improvement of microstructure was also justified by the improved mechanical strength and durability of concrete.



(a) (b)

Figure 16 SEM image of Mix having binary blending with NS at (a) 7 days (b) 28 days

6.Discussion

Adding NS to concrete can alter its rheological properties. Replacement of NS can improve the mechanical and durability aspects of concrete. As per the investigation conducted, it can be summarised that the blended mix with NS showed significant improvement in terms of mechanical strength and durability criteria as well. *Figure 4* and *Figure 5*, *Figure 6* and *Figure 7*, *Figure 8* and *Figure 9* for acid test, sulphate test and chloride test respectively show that when the percentage of NS goes up, the percentage of strength loss goes down, but when the ratio of weight to body size goes up, the percentage of strength loss goes up a lot. It is possible that the fact that NS concrete is pozzolanic is what makes it so resistant to acid attack. Due to finer particle size and high specific area, NS shows very high pozzolanic activity, it not only works as a filler material, but also as an activator to pozzolanic reaction, which were evident from the SEM study of NS blended HSC. *Figure 10* and *Figure 11* shows the percentage increase in flexural strength as compare to control mix for different w/b ratio with varying percentage of NS at 28 days. Similarly, *Figure 13* and *Figure 14* shows the percentage increase in split tensile strength as compare to control mix for different w/b ratio with varying percentage of NS at 28 days Split tensile strength test and flexural strength test also indicated improvement in the mechanical strength of the blended mix. Similarly, the results obtained from the acid resistance test, sulphate resistance test and chloride resistant test also shows the improved resistance of concrete toward the chemical attack. SEM image as shown in *Figure 16* also indicates the improvement in the microstructure of the concrete after the inclusion of NS in the blended mix. The results of this study are based upon the six tests that have been undertaken. However, due to unavailability of the instruments tests like rapid chloride penetration test (RCPT), gas permeability test and chloride diffusion test including Nord-test method could not be performed and may be considered for further research.

A complete list of abbreviations is shown in *Appendix I.*

7.Conclusion and future work

As per the experimental findings, it can be stated that the percentage reduction in compressive strength as well as the weight of the cube specimen after chemical attack increases as the percentage of NS in the concrete mix decreases. However, the rate of reduction in percentage weight and strength decreases after 1.5% NS inclusion. Therefore, the optimal dose for the best resistance to chemical attack is 1.5% NS replacement level. Additionally, it may be inferred that when the w/b ratio decreases, so does the percentage of strength and weight loss. However, the concrete becomes unworkable when the w/b ratio is reduced by more than 0.36. NS inclusion in concrete shows tremendous improvement in strength and durability properties of concrete, but due to its higher cost its use is restricted to high strength concrete (HSC) and important concrete structure only. Additionally, significant enhancement in split tensile strength and flexural strength of concrete were observed with increasing percentage of NS, but the rate of percentage increase in strength was maximum for 1.5% NS. Furthermore, the experimental setup in this study focused on the effect of NS, however, other durability indicators have still not been investigated which becomes the limitation of this study. Investigating the effect of using quaternary blending with ground granulated blast furnace slag (GGBS), alccofines and NS on the strength and durability of HSC will help in providing a clear understanding of the possible mix proportions.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Dr. Satish Kumar Chaudhary: Writing, experimental setup and data collection. **Dr. Ajay Kumar Sinha:** Conceptualising the research and supervision. **Dr. Praveen Anand:** Writing draft and data collection.

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Dr. Satish Kumar Chaudhary currently serves as an Assistant Engineer at RCD, Bihar. With a combination of 5 years of field and research experience, he acquired his B.Tech degree from NCE in 2012 and went on to pursue an M.Tech in Structural Engineering from NIT Patna in 2016. He successfully completed his PhD from NIT Patna as well. His primary research interests revolve around concrete, Micro silica, and Nano silica. He holds memberships in esteemed organizations such as the All India Council for Technical Skill Development (AICTSD) and the International Association of Engineers (IAENG). Notably, he possesses extensive expertise in quality monitoring of Road Design and MATERIals.

Email: satish.ce16@nitp.ac.in

Dr. Ajay Kumar Sinha currently holds the position of Professor in the Civil Engineering Department at the National Institute of Technology Patna. With an impressive 37 years of teaching and research experience, he earned his B.Tech degree from IIT BHU in 1986. Furthering his academic journey, he completed his M.E. in Earthquake Engineering from IIT Roorkee in 1989, and later accomplished his PhD from Delhi College of Engineering, University of Delhi. Dr. Sinha's research interests encompass a wide range of areas including Seismic Resistant Structures, Vulnerability Assessment and Retrofitting of Structures, Structural Health Monitoring, and Reliability Engineering. Notably, he serves as the Center Director cum Nodal Officer of the Earthquake Safety Clinic and Center at NIT Patna. He is also a distinguished member of the Earthquake Committee of BSDMA, GoB, Patna. With an impressive academic portfolio, Dr. Sinha has contributed significantly to the field of civil engineering. He has published over 155 research papers in both national and international journals and conferences. Additionally, his mentorship extends to supervising 7 PhD and 60 ME students, with an additional 10 PhD candidates currently under his guidance.

Email: aksinha@nitp.ac.in

Dr. Praveen Anand earned his B.Tech degree in Civil Engineering in 2015 from West Bengal University of Technology, India. He pursued his M.Tech with a specialization in structural engineering from the National Institute of Technology, Patna. In 2022, he successfully completed his Ph.D. at the National Institute of Technology, Patna. Dr. Anand has maintained an affiliation with the Earthquake Safety and Clinic Centre (EQSC) at NIT Patna. He also served as a Guest Assistant Professor at Government Engineering College, Jehanabad. His primary area of interest revolves around Retrofitting and Strengthening, as well as Vulnerability Assessment and Seismic Analysis of Structures.

Email: praveen.ce16@nitp.ac.in

Appendix I

S. No.	Abbreviation	Description
1	CA	Coarse Aggregate
2	CNS	Colloidal Nano Silica
3	CSH	Calcium Silicate Hydrate
4	FA	Fine Aggregate
5	FM	Fineness Modulus
6	G	Specific Gravity
7	GGBS	Ground Granulated Blast Furnace Slag
8	HRWR	High-Rate-Water-Reducer
9	HSC	High Strength Concrete
10	IS	Indian Standards
11	NS	Nano Silica
12	OPC	Ordinary Portland Cement
13	RCPT	Rapid Chloride Penetration Test
14	SCM	Supplemental Cementitious Materials
15	SEM	Scanning Electron Microscope
16	w/b	Water-Binder