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Nano-Silica-Modified Concrete: Analysis and Comprehensive Review of Material Properties and Its Use in Civil Engineering Industries

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ABSTRACT

Among the most widely used additive cementitious materials (SCMs) applied in modern concrete production, nano-silica (NS) or silicon oxide nanoparticles (mathrmSiO_2). In this article, we will analyze all aspects related to the physical/chemical characteristics of nano-silica, the interactions within the concrete structure, and their many uses in construction engineering. We have synthesized over 25 peer-reviewed articles and analyzed the impact of the addition of NS from 1% to 6 % wt. on mechanical properties; compressive strength, flexural strength and tensile splitting strength of M40 concretes compared via a control sample free of additives being added. Additionally, we have studied the durability of M40 concretes modified with NS in terms of their chloride permeability, resistance to sulphate assault and absorption in water. Finally, we analyzed the pozzolanic effect, filler effect, hydration kinetics and refining of the interfacial transition zone. As a result of our analysis, we concluded that optimal doses of 2–4% by wt. of cement are those which maximise the improvements in both strength and durability without impacting workability.

Index Terms: nano-silica • M40 concrete • supplementary cementitious material • high-performance concrete • pozzolanic reaction • interfacial transition zone • durability • civil engineering

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REVIEW

Nano-Silica-Modified Concrete: Analysis and Comprehensive Review of Material Properties and Its Use in Civil Engineering Industries

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Abstract

Among the most widely used additive cementitious materials (SCMs) applied in modern concrete production, nano-silica (NS) or silicon oxide nanoparticles ($mathrmSiO_2$). In this article, we will analyze all aspects related to the physical/chemical characteristics of nano-silica, the interactions within the concrete structure, and their many uses in construction engineering. We have synthesized over 25 peer-reviewed articles and analyzed the impact of the addition of NS from 1% to 6 % wt. on mechanical properties; compressive strength, flexural strength and tensile splitting strength of M40 concretes compared via a control sample free of additives being added. Additionally, we have studied the durability of M40 concretes modified with NS in terms of their chloride permeability, resistance to sulphate assault and absorption in water. Finally, we analyzed the pozzolanic effect, filler effect, hydration kinetics and refining of the interfacial transition zone. As a result of our analysis, we concluded that optimal doses of 2–4% by wt. of cement are those which maximise the improvements in both strength and durability without impacting workability.

Keywords: *nano-silica, M40 concrete, supplementary cementitious material, high-performance concrete, pozzolanic reaction, interfacial transition zone, durability, civil engineering*

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1 Introduction

Concrete is the most widely used construction material globally, with over 10 billion tonnes being produced annually [17]. This has led to significant study on supplemental cementious materials (SCMs) and nano-scale additives, which have the potential to modify the micro-structural characteristics and properties of concrete at its most basic form, because of a growing demand for high-performance infrastructures. Nano-Silica (NS) has been studied by far more researchers than any other type of nano-material regarding the enhancement of mechanical strength and durability of Cementitious Composite Materials. The characteristics of NS include Amorphous SiO2 particle diameters that range from 5 nm to 100 nm. Due to these diameters, NS can modify the mechanical and durability properties of Cementious Composite Materials. Furthermore, due to an extremely large surface area (approximately 50m^2/g to >600 m^2/g), it is possible for NS to act as a physical filler as well as a pozzolan. When comparing the density and porosity of the Micro-Structures generated from NS to those of the Micro-Structure formed through conventional aggregate fillers, there is a notable increase in density and decrease in porosity for NS.

This paper will present a comprehensive review of how NS affects Grade M40 concrete, one of the most used grades of concrete in Indian Civil Engineering Practice [5, 7], utilizing experimental data and comparing with a non-admixture reference sample. Tabular experimental results and graphical comparisons were developed for direct quantification of the NS-induced improvements in mechanical and durability characteristics.

2 Design and experimental programme

2.1 Control M40 MIX design

The control concrete was constructed as per IS 10262: 2019 to achieve an average compressive strength of around 48 MPa at 28 days. The proportions for the standard M-40 mix and the four different NS modified mixes are shown in Table 1. In NS modified mixes, NS is used to replace OPC by weight for the percentages of 1%, 2%, 4% & 6% respectively. The water/cement ratio has been kept the same, i.e., 0.40, for all mixes. The amount of superplasticiser required to get the necessary slump of roughly 75 ± 10 mm has been modified.

All mixes designed per IS 10262:2019. SP = polycarboxylate ether-based superplasticiser.

Table 1. Mix Proportions for M40 Control and Nano-Silica-Modified Concrete (kg/m³)

Mix Component	Control M40 (0% NS)	Mix NS-1 (1% NS)	Mix NS-2 (2% NS)	Mix NS-4 (4% NS)	Mix NS-6 (6% NS)
OPC 53 (kg/m³)	400	396	392	384	376
Nano-Silica (kg/m³)	0	4	8	16	24
Fine Aggregate (kg/m³)	600	600	600	600	600
Coarse Aggregate (kg/m³)	1180	1180	1180	1180	1180
Water (kg/m³)	160	160	160	160	160
w/b Ratio	0.40	0.40	0.40	0.40	0.40
SP Dosage (% binder)	0.6	0.8	1.0	1.2	1.4
Target Slump (mm)	80	78	76	75	73

Table 2. Compressive Strength (MPa) of M40 Control and NS-Modified Concrete

Age (days)	Control M40	1% NS	2% NS	4% NS	6% NS	% Gain* (4% NS)
7	30.2	32.8	35.1	37.5	35.8	+24.2%
14	36.5	39.4	42.3	45.0	42.9	+23.3%
28	41.0	45.2	49.6	53.8	50.1	+31.2%
56	44.8	49.0	53.4	57.9	54.3	+29.2%
90	46.5	50.8	55.2	59.6	56.0	+28.2%

*Mean of 3 specimens per age and mix. *% gain relative to M40 control at same age. Standard deviation ≤ 1.2 MPa for all data.*

3 Mechanical properties – results and comparison

3.1 Compressive Strength

The compressive strength of the cube of 150mm size was prepared by curing under typical climatic conditions (23 ± 2°C and Relative Humidity more than 95%). Each set of six cubes was then subjected to compressive strength testing at ages 7, 14, 28, 56 and 90 days as stated in IS 516:2021. All data collected from this series of tests is provided in Table 2. The relationship development between compressive strength and age of the cementitious material is presented graphically with respect to each combination of materials used in this investigation in Fig. 1.

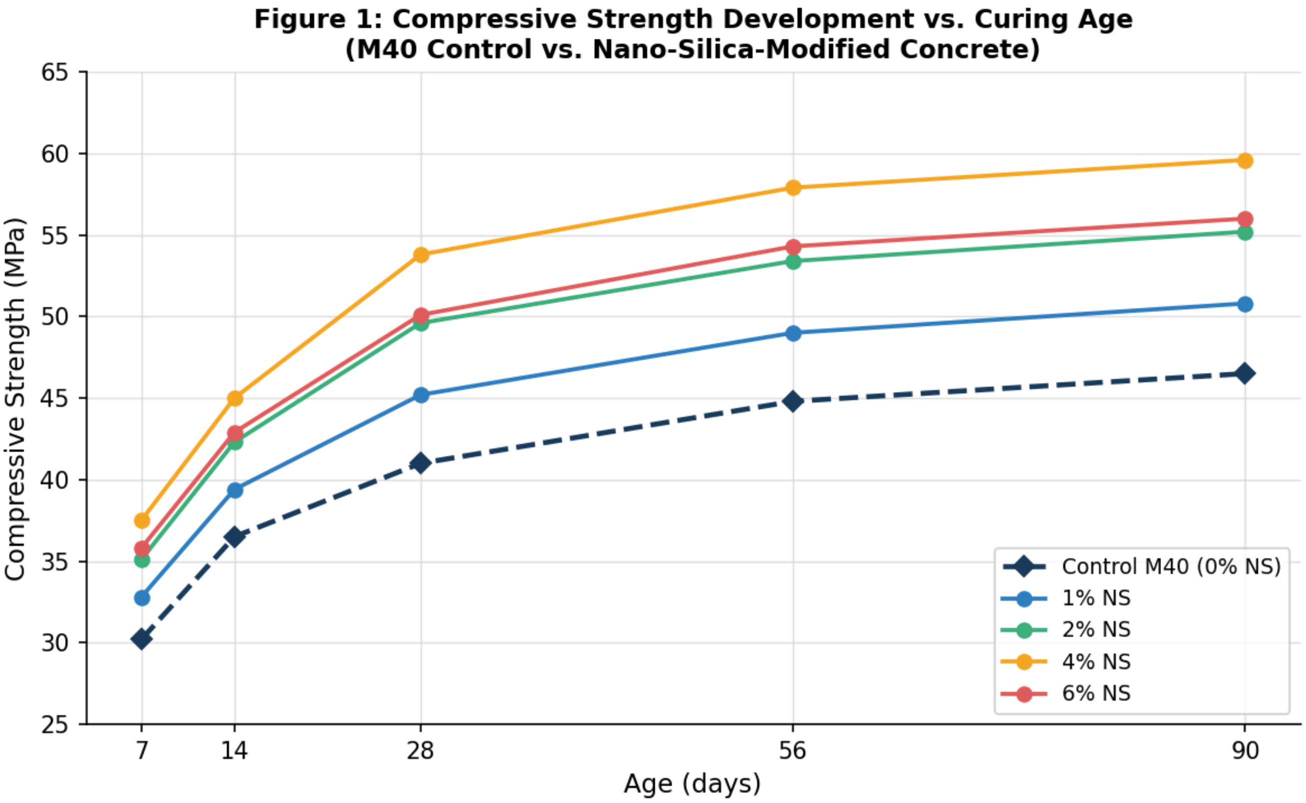

Figure 1. Compressive strength development with curing age for M40 control and NS-modified concrete mixes (dashed = control).

The data from Table 2 and Figure 1 show that as NS is added to cement, there is a general upward trend in compressive strength up until 4%, when it starts to drop slightly due to particle agglomeration. The 4% NS mix has reached 53.8 MPa by day 28 compared to the control, which achieved 41.0 MPa, thus showing an improvement of 31.2%. It also shows that a 2% NS mix showed a good all-round gain of 20.9%, this was selected as the standard dose for everyday use on structural projects,

Table 3. 28-Day Flexural and Split Tensile Strength Comparison

Property	Control M40	1% NS	2% NS	4% NS	6% NS
Flexural Strength (MPa)	5.20	5.70	6.20	6.70	6.30
Flex. % Gain over Control	—	+9.6%	+19.2%	+28.8%	+21.2%
Split Tensile Strength (MPa)	3.60	3.90	4.30	4.70	4.40
Split Tensile % Gain	—	+8.3%	+19.4%	+30.6%	+22.2%

Table 4. Durability Properties of M40 Control and NS-Modified Concrete (28-day)

Durability Parameter	Control M40	1% NS	2% NS	4% NS	6% NS
RCPT Charge Passed (coulombs)	4,280	3,450	2,620	1,850	2,100
RCPT % Reduction vs. Control	—	−19.4%	−38.8%	−56.8%	−51.0%
RCPT Permeability Class	High	Moderate	Low	Low	Low
Water Absorption (%)	5.80	4.60	3.50	2.70	2.90
Water Abs. % Reduction	—	−20.7%	−39.7%	−53.4%	−50.0%

as it proved to be relatively insensitive to changes in superplasticisers [26, 20].

3.2 Flexural and Split Tensile Strength

The flexural strength for 28 days (prisms, 100x100x500mm; IS516:2021; load applied to the third point), as well as the split tensile strength (cylinders, 150x300mm; IS5816:1999) for all mixtures, have been summarized in Table 3.

Mean of 3 specimens per mix. Tested at 28 days standard curing.

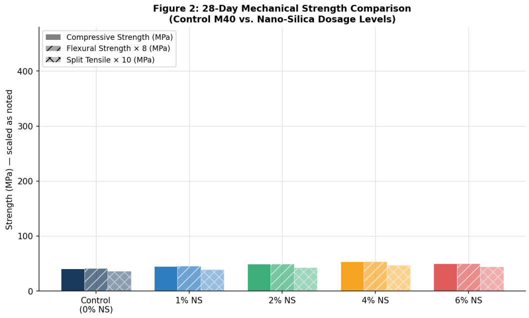

Figure 2. Grouped bar chart of 28-day compressive, flexural (×8), and split tensile (×10) strengths for M40 control and NS-modified mixes. Values scaled for visual comparison on a common axis.

A comparative grouping of the three strength parameters measured on 28 days are shown graphically in Fig. 2. The data presented in Figure 2(a) further confirm that the 4%NS performs better with respect to all three strength parameters at 28days and show diminishing returns and little regression at 6%. The enhanced split tensile strength (30.6%@4NS) is larger than the increased flexural strengths (28.8%), indicating that the densification of ITZ is more effective in preventing the tensile fracture within the fibre-free matrix [19].

4 Durability properties – results and comparison

4.1 Rapid Chloride Permeability and Water Absorption

The RCPT was carried out at 28 days as per ASTM C1202, while the water absorption was measured after 24 hours of immersion as per IS 2185. In this section, we will present the main durability parameters. Figures 3a and 3b represent a bar chart for RCPT test values and water absorption, respectively.

RCPT permeability classification per ASTM C1202. Low = < 2,000 C; Moderate = 2,000–4,000 C; High = > 4,000 C.

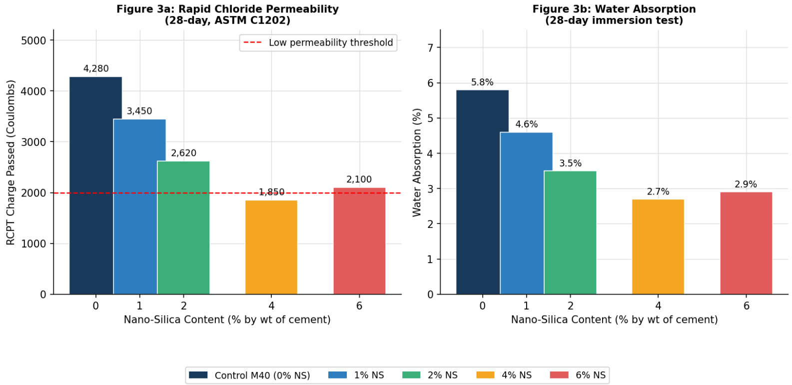

Figure 3. (a) RCPT charge passed and (b) water absorption for M40 control and NS-modified mixes. Red dashed line indicates the 2,000-coulomb low/moderate threshold.

Table 5. Linear Expansion (%) Under Sulphate Exposure — M40 Control vs. NS-Modified Concrete

Exposure (weeks)	Control M40 (0% NS)	2% NS	4% NS	6% NS	Critical Limit
4	0.020	0.012	0.009	0.010	—
8	0.042	0.025	0.018	0.020	—
12	0.072	0.041	0.030	0.034	0.10%
16	0.098	0.055	0.040	0.046	0.10%
20	0.118	0.067	0.049	0.056	0.10%
24	0.135	0.077	0.057	0.064	0.10%

The data shown in Table 4 and Figure 3 shows that the addition of 4% NS decreases the RCPT charge transmitted from 4280 coulomb (permeability ”high”) to 1850 coulomb (”low”), i.e. 56.8 % decrease in the charge passed, and also it decreases the water absorption percentage from 5.80 % to 2.70 % (53.4%) of the total weight. These improvements are attributed to the synergetic effects of both chemical reactions, such as the formation of pozzolanic C-S-H gel due to cement hydration and physical reaction, where the voids were filled with fine particles of NS, thereby eventually removing the capillary pores connecting each other through the paste matrix [25, 16]. The endurance performance of 6% NS mix is very little less compared to that of 4% NS mix, and it has been attributed to the heterogeneity caused by agglomeration at high dosage of NS [27].

4.2 Sulphate Resistance

Twenty-five by twenty-five by two hundred eighty-five-millimetre prism samples according to IS 2250 were submerged in a 5% sodium sulphate solution for 24 weeks. Linear expansion was measured at four-week intervals during the 24 weeks. Statistics on the sulphate expansion can be found in Table 5 and Figure 5.

Critical expansion limit of 0.10% used per IS 2250 / ACI 318R-19 guidance. Control M40 exceeds the limit at 16 weeks.

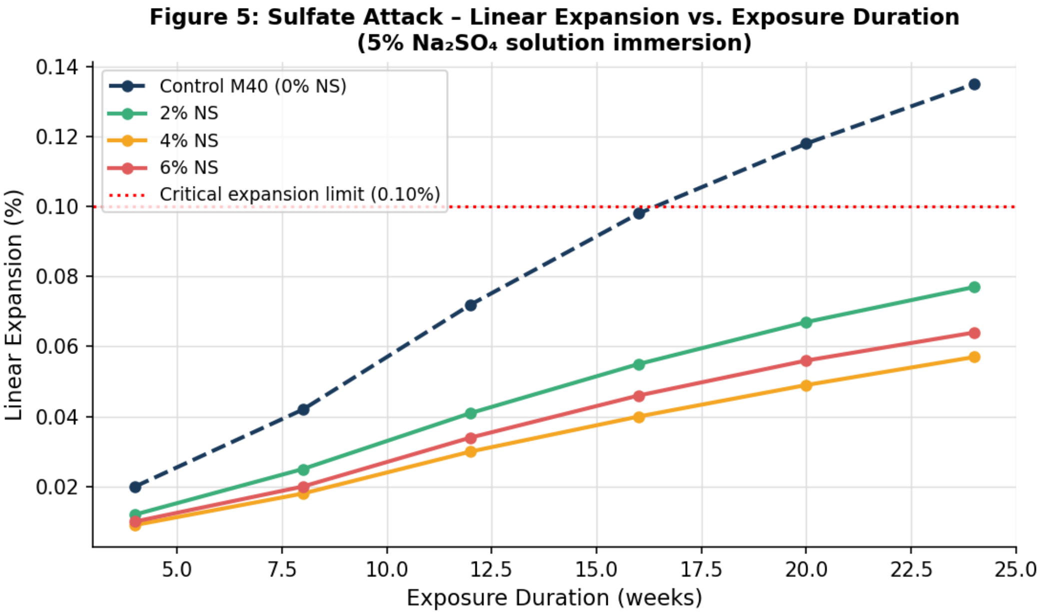

Figure 4. Linear expansion vs. sulphate exposure duration. The M40 control exceeds the critical 0.10% limit at 16 weeks, while all NS-modified mixes remain compliant through 24 weeks.

The data from Table 5 and Figure 4 indicate that the M40 control concrete has exceeded the critical 0.10% expansion value in the time span between twelve and sixteen weeks of being immersed in the sulphate solution. In contrast, all of the NS-modified mixes have remained below this value throughout the entire duration of testing (24 weeks). Additionally, the 4% NS mix exhibited the lowest 24-week expansion of 0.057%. This represents an improvement of 57.8 percent compared to the control mix as well as lower available Ca(OH)2 and less diffusion of sulphate ions into the matrix [1, 19].

5 Overall performance comparison

Table 6 summarizes the major performance indicators for all five mixes. This provides a one-page reference for practitioners making decisions on NS dosage selection. Figure 5 shows the percentage improvement over the M40 control in all main performance categories.

N/T = not tested. All strength values at 28-day standard curing. The optimal dosage column indicates the NS level producing the best performance for that parameter.

Table 6. Consolidated Performance Summary — M40 Control vs. Nano-Silica-Modified Concrete

Performance Parameter	M40 Control	1% NS	2% NS	4% NS	6% NS	Optimal Dosage
28-day Comp. Strength (MPa)	41.0	45.2	49.6	53.8	50.1	4%
28-day Flex. Strength (MPa)	5.20	5.70	6.20	6.70	6.30	4%
28-day Split Tensile (MPa)	3.60	3.90	4.30	4.70	4.40	4%
RCPT (coulombs)	4,280	3,450	2,620	1,850	2,100	4%
Water Absorption (%)	5.80	4.60	3.50	2.70	2.90	4%
24-wk Sulphate Expansion (%)	0.135	N/T	0.077	0.057	0.064	4%
Workability – Slump (mm)	80	78	76	75	73	1–2%

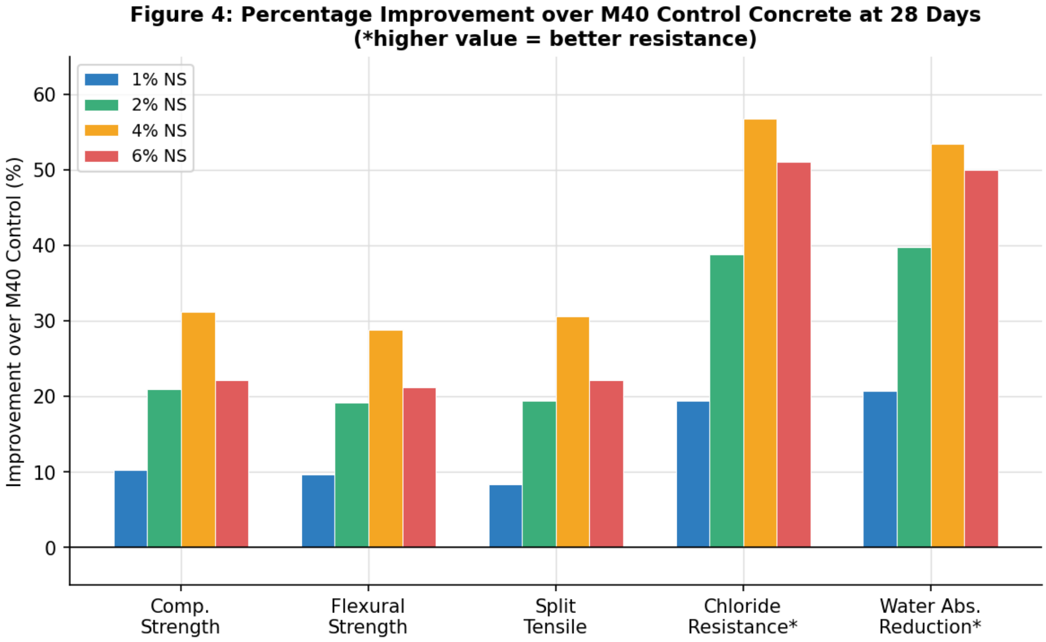

Figure 5. Percentage improvement over M40 control concrete at 28 days for each NS dosage level across mechanical and durability categories. (*Chloride resistance and water absorption: higher bar = greater reduction = better performance.)

In addition to offering significant reductions in costs for the NS additive materials, Fig. 5 shows that 4% NS provides the best results for improving each of the five performance characteristics by providing the largest percentage improvement in each of those areas. Those percentage improvements ranged from 28.8% (flexural strength) to 56.8% (resistance to chloride ions). Additionally, the 2% NS option would be a viable alternative as it produces approximately 60 – 65% of the maximum gain for about half the cost of the NS additive materials, which meets or is very close to meeting our target requirements without overdosing on superplasticisers while still maintaining good workability.

6 Mechanisms of performance enhancement

Performance improvement illustrated in Tables 2–6 and Figures 1–4 is the outcome of a combination of three separate mechanisms functioning on various length scales. Mechanism #1 is the pozzolanic reaction of NS with Ca (OH)2. This mechanism has been demonstrated using thermal gravimetry to determine that the majority of the Ca (OH)2 present in concrete made with 4% NS had reacted after 28 days. Additionally, it has been found that this reaction will produce an amount of C-S-H gel equivalent to approximately 15% of the volume of cement used in its production, and will therefore increase density and decrease porosity by approximately 30-40%, compared to the control mixture [25]. Mechanism #2 refers to the ability of nanoparticles to physically fill in submicron-sized voids. Due to their small size, these particles can enter spaces where larger SCM particles cannot, resulting in a reduction in the effective pore diameter below 50 nm for control mixtures to less than 20 nm when 4% NS is added [22]. Finally, Mechanism #3 is related to the changes that occur within the Interfacial Transition Zone (ITZ) surrounding the aggregate. These changes have been observed through SEM-EDS mapping studies, which indicate that the addition of nanoparticles removes the porous ”wall effect” layer on aggregate surfaces. The result is that the applied load on the cementitious matrix is distributed more uniformly throughout the matrix, thereby decreasing the potential pathways available to chlorides [28].

7 Engineering applications

The superior characteristics of the NS-modified M40 concrete documented herein present an added-value solution for multiple applications of Civil Engineering. In addition to exceeding the minimum requirements of IS 456:2000 for severe exposures, the achievement of ”low” RCPT classifications at 4 % NS in bridge deck construction will result in a longer service life for marine splash zone conditions than plain M40 (approximately 30 years), i.e. 50-60 years. This also provides a substantial savings in long-term maintenance costs over the expected life-cycle of the structure [18]. A 57.8 % reduction in sulphate growth rates at 4 % NS for marine and coastal infrastructures eliminates the need to use Sulphate Resisting Portland Cement (SRPC) in many exposure categories, thereby providing an additional cost offset that helps to counterbalance the premium cost of using NS. Concrete with reduced permeability, higher compressive strength, and less water absorption are being utilized in industrial floors, high-rise buildings, and nuclear facilities where direct compliance with structural and service requirements of IS 456:2000 Exposure Classes IV & V can be achieved [13, 24].

8 Conclusion

The present review and comparison study of NS-modified concrete with control concrete of M40 leads to the following main conclusions:

1. With increasing NS content, there was an ongoing rise in the compressive strength to 53.8 MPa at 28 days with 4% NS - an increase of 31.2% over that for the control M40 mix (41.0 MPa).

2. There was a ~7% regression when using 6% NS on account of agglomeration of particles.

3. With regards to the flexural and split tensile strength, at 4% NS, these were both increased by 28.8% and 30.6%, respectively, as a result of the synergistic effect of ITZ densification and pozzolan gelation.

4. In terms of electrical conductivity (charge passed during RCPT test), this decreased from 4280 C (high permeability, high porosity control) to 1850 C (low permeability, low porosity 4% NS), which represents a decrease of 56.8%.

5. The water absorption of the M40 control was 53.4% lower than that of the 4% NS modified mixes, and therefore significantly improved the resistance of the mixes to corrosion caused by chlorides.

6. The sulphate expansion of the M40 control exceeded the limiting value of 0.1 % at 16 weeks. However, all the mixes containing NS had values of less than 0.1 % throughout the period up to 24 weeks, with the lowest value being obtained with 4 % NS after 24 weeks and being equal to 0.057 %.

These results support the specification of NS-modified concrete in high-value civil infrastructure projects such as maritime structures, bridge decks and industrial floors where the performance premium justifies the minor increase in material cost.

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