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Original Article

Augmented Properties of High Strength Self Compaction Concrete Partially Replaced with Nano Mineral Admixtures

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Abstract *- The construction industry continually evolves to meet the demand for more robust, durable, and sustainable concrete structures. To improve the mechanical and durability qualities of High-Strength Self-Compacting Concrete (HSSCC), this study examines the application of nano minerals as a partial substitution for cement. Fly ash, Silica Fume, Phosphogypsum, and Alccofine are examples of nanomineral admixtures used to improve concrete performance while reducing the environmental impact of regular cement. The experimental program encompasses a series of laboratory tests to assess the fresh concrete and mechanical attributes of the nano-modified HSSCC. Concrete samples curing for seven, fourteen and twenty-eight days will be utilized for these strength tests. The RCPT test, which gauges chloride ion penetration in concrete for twenty-eight, fifty-six and ninety days of curing, is conducted similarly. Tests like Flowability, L-Box, V-Funnel, J ring and V funnel at T5 minutes are among the tests on freshly built concrete. These tests are helpful for determining how well new concrete flows, passes over obstacles and resists segregation. The outcomes show that utilizing nanomineral admixtures dramatically improves the performance of HSSCC. Compressive strength and durability are notably increased, surpassing conventional HSSCC mixes, and the modulus of elasticity shows improvement, reflecting enhanced stiffness, durability and structural integrity.*

Keywords *- Fly ash, Silica fume, Phosphogypsum, Alccofine, L-box, V-funnel, J-ring, Compressive strength, Modulus of elasticity, RCPT, Structural integrity*.

1. Introduction

Concrete, among the most ubiquitous construction materials, has been subject to continuous innovation and enhancement to meet the ever-increasing demands for more vital, durable, and sustainable structures. High-Strength Self-Compacting Concrete (HSSCC) represents a notable advancement in concrete technology, offering improved workability, reduced labour requirements, and enhanced structural performance. Yet, the conventional production of HSSCC relies heavily on Portland cement, a material associated with high carbon emissions and environmental impact. Researchers and industry professionals have focused on alternative materials and technologies in pursuing more sustainable construction practices. This study delves into a novel approach to address this challenge by exploring the incorporation of nano mineral admixtures as partially replaced cement in HSSCC. Nano-sized materials, in the form of Fly-Ash (FA), Silica Fume (SF), Phosphogypsum (PG), and Alccofine (AC), have garnered considerable attention due to their unique properties and potential to revolutionize the properties of traditional concrete. When skillfully integrated into concrete mixtures, these materials promise to enhance the mechanical and durability properties of HSSCC while reducing its environmental footprint.

The drive for sustainability in the construction industry has never been more urgent, with climate change and resource scarcity casting a long shadow over the built environment. Since cement production contributes significantly to the world's carbon dioxide emissions, it is critical to look for creative solutions without sacrificing the strength and functionality of concrete structures.

Nano mineral admixtures, with their ability to enhance properties and reduce the cement content, represent a compelling avenue for achieving this delicate balance. Through experimentation and analysis, this study aims to ascertain how nano-mineral admixtures work affect the characteristics of HSSCC. Despite its with lower compressive strength, fly ash is one of the replacement materials for cement that can help reduce environmental hazards [1]. Conventional concrete and Self-Compacting Concrete (SCC) exhibit significantly different rheological characteristics due to their distinct composition, mix design, and flowability requirements [2]. The inclusion of mineral additives like Fly Ash and Copper Slag, which mainly were substituted with cement and fine aggregate, increased the density of SCC, according to SEM examination [3]. By replacing up to 12.5% of cement in the concrete mix with silica fume, the thickness of the concrete will be somewhat improved [4].

The mechanical qualities are enhanced by adding silica nanoparticles and silica fume to mineral admixtures [5]. Concrete gains more strength when silica fume is added in more significant quantities [6]. Replacing phosphogypsum up to 5% increases the durability property significantly [7]. There has been a methodological movement in concrete design from a strength-based approach to a performance-based one [8].

Globally, an alternative to concrete is a significant finding nowadays. In this research, an attempt was made to partially replace the cement particles with nanomineral admixtures and find the optimal dosage. Because of the addition of nano minerals, the strength may be increased to some extent due to their ingredients. Detailed testing was carried out, and the test results were tabulated. Moreover, if this alternative becomes effective, it may be used for major works and reduce the impact of global warming. In a world where construction practices must adapt to meet the challenges of the 21st century, the exploration of nano mineral admixtures in HSSCC represents a vital step forward in pursuing superior building materials that are environmentally responsible and technologically advanced. This study underscores the significance of such research and sets the stage for a comprehensive investigation into the enhanced properties of HSSCC by utilizing nanomineral admixtures.

2. Materials Used

2.1. Fly Ash

An ordinary residue of the burning of pulverized coal in power plants is Fly Ash (FA) [9]. The mineral impurities in coal suspended during combustion and with the flue gases from the combustor include feldspar, clay, shale, and quartz. Fly ash is composed of cooled, melted materials that, as they rise, solidify into glassy, spherical particles. Bag filters are used to remove fly ash from exhaust emissions.

2.2. Silica Fume

Amorphous (non-crystalline) silicon dioxide is known as micro silica, commonly called silica fume. It is an ultrafine powder that results from silicon and ferrosilicon alloy manufacturing. It is nearly 100 times smaller than typical cement particles and has a particle size of less than 1 micron and an average diameter of 0.1 microns.

The material’s high (>90%) amorphous silica concentration affects its behaviour. At temperatures up to 2,000°C, high-purity quartz is converted to silicon, generating SiO_2 vapours that oxidize and condense as minute non-crystalline silica particles in the low-temperature region [10].

2.3. Phosphogypsum

Phosphogypsum (PG) is a by-product of the wet process used in the chemical and phosphate fertilizer industries to make phosphoric acid. Gypsum ($CaSO_4$•$2H_2O$) makes up the majority of it. The dehydrate technique is used to manufacture the majority of phosphogypsum in India because it is easier to operate and requires less maintenance than other methods.

2.4. Alccofine

Alccofine is a brand-new, micro-fine material made in India that contains much smaller particles than conventional hydraulic substances like cement, fly ash, silica, etc. Alccofine provides unique qualities that improve the “performance of concrete” in the fresh and hardened stages because of its optimized distribution of particle sizes. It can be used as a practical substitute for silica fume due to its appropriate particle size distribution-not too coarse. Its characteristic feature, an optimum particle size distribution, is created during manufacturing utilizing specific equipment in precisely controlled conditions. Alccofine versions 1203 and 1101 have low and high calcium silicate content, respectively. The letters 1201, 1202, and 1203 of the Alccofine 1200 series stand for fine, microfine, and ultrafine particle sizes. Because Alccofine 1203 is so ultra-fine, less water is needed to make it work, even up to 70% replacement level when necessary.

2.5. Auramix 400

Aura Mix 400 is a novel blend of superplasticizers of the most current generation, built on a poly-carboxylic ether polymer [11] with long lateral chains. The dispersion of cement is substantially improved. It combines the reduction of water with the retention of workability. It is used to make highly effective and incredibly workable concrete.

2.6. Chemical Composition of Nano-Minerals

The chemical composition of different nanomaterials used in this research is shown in Table 1.

3. Material Tests

Sustainable building materials must be used for a structure to be considered green. The construction industry has turned to sustainable materials to create more substantial, environmentally friendly buildings. These materials are chosen and developed to minimize environmental consequences from extraction and manufacture to transportation and disposal [21]. Materials like steel and wood that have been previously used reduce the need for new resources and divert rubbish from landfills. Table 1 lists some eco-friendly options.

3.1. Specific Gravity Test

The specific gravity test is a typical laboratory test to ascertain a material's density or relative density concerning the thickness of a reference substance, typically water. This test is essential because it helps evaluate the qualities and features of materials, which is vital in many industries, including civil engineering, geology, construction, and materials science. Table 2 lists the specific gravity values for several materials.

3.2. Fresh Concrete Test

Fresh concrete tests are carried out to evaluate the workability, consistency, and other qualities of freshly mixed concrete before it sets and hardens.

These tests are essential to ensure the concrete mixture complies with the specified standards and can be put and compacted correctly on the construction site. Table 3 contains the test results for recently placed fresh concrete.

Table 1. Chemical composition of nano-minerals

Chemical Composition	Fly Ash (FA)	Silica Fume (SF)	Phosphogypsum (PG)	Alccofine (AC)
C	23.29	-	-	-
CaO	3.00	0.31	33.81	33
SiO_2	36.10	93.67	4.33	35
Al_2O_3	25.03	0.83	0.03	22.1
FeO	8.66	1.30	0.02	2.1
MgO	1.24	0.84	0.005	7.5
Na_2O	-	0.4	0.002	-
SO_3	0.29	-	48.31	0.3
K_2O	0.84	1.10	0.3	-
L.O.I.	1.55	1.55	13.12	-

Table 2. Specific gravity values of materials

Sl. No.	Description	Specific Gravity Values
1	Cement	3.14
2	Fine Aggregate	2.62
3	Coarse Aggregate	2.72
4	Fly Ash	2.14
5	Silica Fume	2.60
6	Phosphogypsum	2.04
7	Alccofine	2.82

Table 3. Fresh concrete test values

Sl. No.	Description	0% PG & AC	2.5% PG & AC	5% PG & AC
1	Flow Test	635 mm	652 mm	641 mm
2	L Box	0.82	0.95	0.90
3	V Funnel	10.8 secs	8.2 secs	9.3 secs
4	V5	15.5 secs	13.8 secs	14.6 secs
5	J Ring	598 mm	625 mm	612 mm

4. Mix Proportion

With concrete and other building materials, the word "mix proportion" refers to the systematic determination and specification of the amounts of different ingredients or components that make up a combination. These ingredients typically consist of binding material (cement), filler materials (such as sand and gravel), water, and sometimes various additives or admixtures. Mix proportioning is a crucial phase in manufacturing concrete or mortar because it directly impacts the characteristics and functionality of the finished product. In this study, Aura Mix 400 is employed as a superplasticizer, and nano-mineral admixtures are used to substitute cement. Table 4 displays the mix design values.

5. Strength Test Results

Tests on hardened concrete are performed to evaluate the qualities and characteristics of concrete after it has cured and reached the desired strength. These tests are necessary to confirm that the concrete satisfies the design criteria, durability specifications, and expectations for overall performance.

5.1. Compressive Strength

Compressive strength, a fundamental property, determines how long concrete can withstand axial loads (pressing or crushing forces) before failing or seriously deforming. It is one of the most significant characteristics of concrete.

It evaluates the load-bearing capability and structural soundness of concrete components such as columns, beams, slabs, and foundations. The compressive value of the tested concrete specimens is listed in Table 5; a graphic depiction is shown in Figure 1.

Table 4. Mix design values of M70 grade for 1 cubic meter

Sl. No.	Materials	Weight of Materials for 1 Cubic Meter (kg)		
		FA - 27.5% SF - 2.5% PG – 0% AC – 0%	**FA – 22.5% SF - 2.5% PG – 2.5% AC – 2.5%**	**FA – 17.5% SF - 2.5% PG – 5% AC – 5%**
1	Cement	455	455	455
2	Fly Ash	178.75	146.25	113.75
3	Silica Fume	16.25	16.25	16.25
4	Phosphogypsum	---	16.25	32.5
5	Alccofine	---	16.25	32.5
6	Fine Aggregate	637	631	631
7	Coarse Aggregate (20 mm & 10 mm)	931	923	922.5
8	Water	169	169	169
9	Aura Mix 400	7.8	7.8	7.8
10	Mix Ratio	**1:0.98:1.43:0.26**	**1:0.97:1.42:0.26**	**1:0.97:1.42:0.26**

Table 5. Compressive strength values

Tested Specimens Based on the Percentage of Materials Replaced for Cement	Compressive Strength Values (N/mm^2)		
	Seven Days	**Fourteen Days**	**Twenty-Eight Days**
FA – 27.5%, SF – 2.5%, PG – 0%, AC – 0%	49.30	69.25	79.82
FA – 22.5%, SF – 2.5%, PG – 2.5%, AC – 2.5%	55.55	73.34	85.23
FA – 17.5%, SF – 2.5%, PG – 5%, AC – 5%	53.25	70.35	78.26

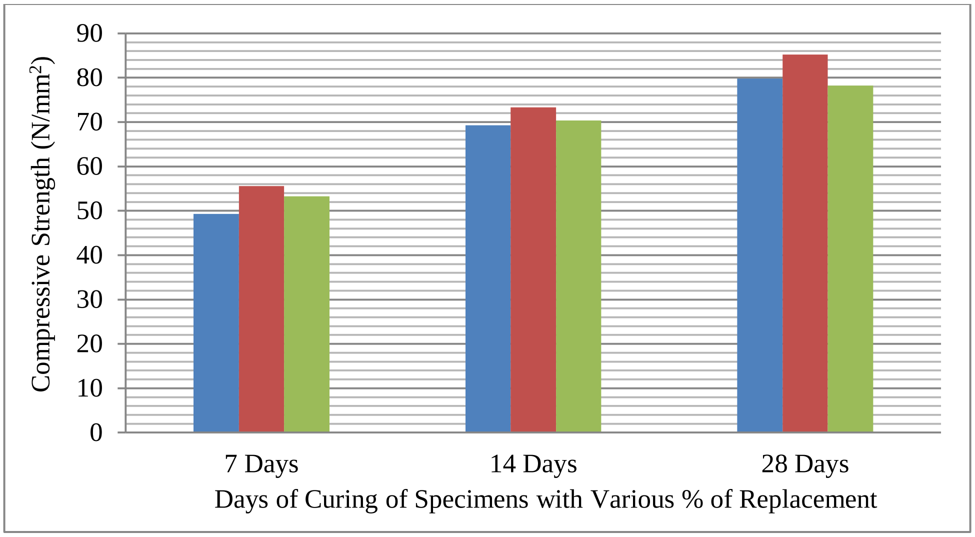

Fig. 1 Compressive strength

Concrete specimens with a 2.5% replacement rate exhibit better outcomes in terms of compressive strength than the other percentages after all days of curing.

The addition of an additional 2.5% of nanomaterials yields results that are comparable to the nominal mix. The table and graph data show that the ideal replacement percentage is between 2.5% and 5%.

5.2. Splitting Tensile Strength

People frequently employ the “Brazilian Test” or “Indirect Tensile Strength Test to evaluate the splitting tensile strength.” It gauges the material’s resistance to tensile stresses applied perpendicular to its surface. It is an essential concrete property, especially when subjected to bending or flexural loads-Table 6 and Figure 2 display the results of the concrete specimens tested in the splitting tensile test.

Table 6. Tensile strength values

Tested Specimens Based on the Percentage of Materials Replaced for Cement	Tensile Strength Values (N/mm^2)		
	Seven Days	Fourteen Days	Twenty-Eight Days
FA – 27.5%, SF – 2.5%, PG – 0%, AC – 0%	3.17	3.50	3.72
FA – 22.5%, SF – 2.5%, PG – 2.5%, AC – 2.5%	2.97	3.86	4.10
FA – 17.5%, SF – 2.5%, PG – 5%, AC – 5%	2.75	3.55	3.83

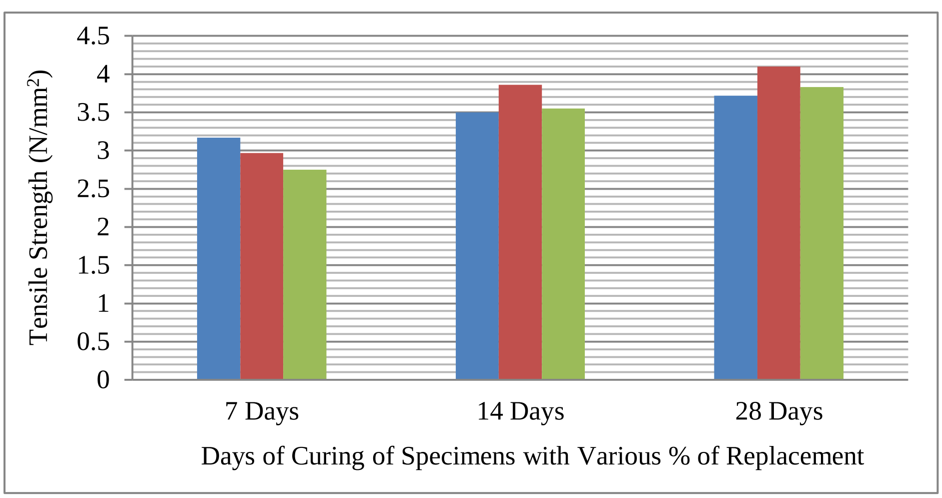

Fig. 2 Tensile strength

The tensile values (shown in Table 6 and Figure 2) are gradually increased in 14 and 28 days of the cure for 2.5% replacement while comparing other mixtures, similar to the compressive strength. The proportion of tensile strength decreases as the percentage of nanomaterials increases.

5.3. Flexural Strength

The ability of concrete to withstand bending or flexural pressures is determined by its flexural strength, also known as the modulus of rupture. Flexural strength examines a concrete's ability to handle transverse loads (bending or tensile pressures) instead of compressive strength, which measures a concrete's resistance to axial loads (pressing or crushing forces). This feature is essential for determining how well concrete performs in applications with considerable bending or flexural stresses, such as beams, slabs, and other structural elements. The flexural strength values are displayed in Table 7 below, and Figure 3 depicts a graphical depiction of those values.

Figure 3 shows that the 2.5% of replacement produces a more robust product than the others. Nano minerals should be present in the mix at a maximum of 5%; any higher proportion leads to a loss in strength. The excess nanomaterials in the mixture may cause this reduction because they cause more significant accumulation than dispersion.

Table 7. Flexural strength values

Tested Specimens Based on the Percentage of Materials Replaced for Cement	Flexural Strength Values (N/mm^2)		
	Seven Days	Fourteen Days	Twenty-Eight Days
FA – 27.5%, SF – 2.5%, PG – 0%, AC – 0%	5.41	7.55	8.54
FA – 22.5%, SF – 2.5%, PG – 2.5%, AC – 2.5%	6.35	9.05	8.98
FA – 17.5%, SF – 2.5%, PG – 5%, AC – 5%	6.10	8.92	8.30

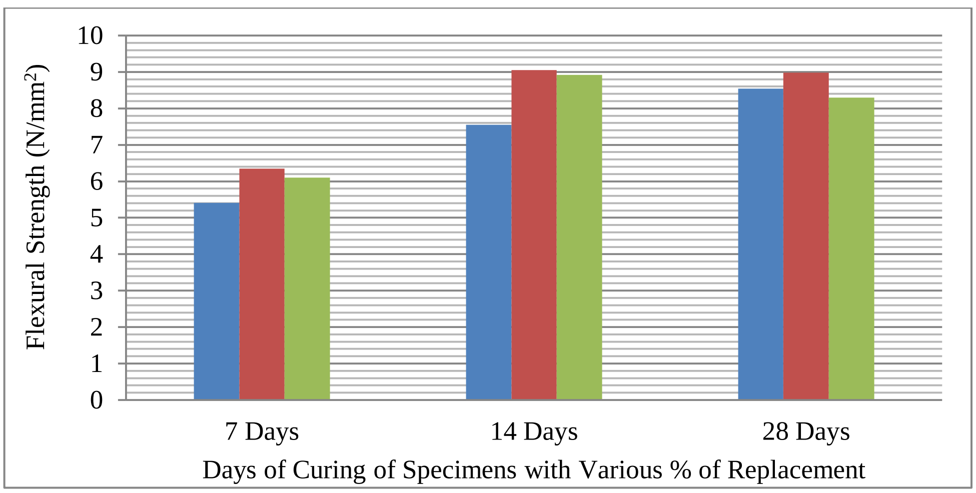

Fig. 3 Flexural strength

6. Durability Test Results

Durability tests assess how well concrete can withstand various environmental and physical stresses over time. These tests are essential for determining concrete buildings' durability and long-term performance.

6.1. Alkaline Test

The 150mm x 150mm x 150mm cube specimens were immersed in sodium hydroxide solution for 28, 56 and 90 days to perform the alkaline test, and the difference in weight loss was recorded in Table 8.

Table 8. Alkaline test values

Tested Specimens Based on the Percentage of Materials Replaced for Cement	Weight of Difference (%)		
	7 Days	14 Days	28 Days
FA – 27.5%, SF – 2.5%, PG – 0%, AC – 0%	6.10	8.92	8.98
FA – 22.5%, SF – 2.5%, PG – 2.5%, AC – 2.5%	5.41	7.55	8.30
FA – 17.5%, SF – 2.5%, PG – 5%, AC – 5%	6.35	8.35	8.54

The cast specimens underwent a 28, 56 & 90-day cure in 3% sodium hydroxide. This testing indicates specific concrete mixes' resistance to sulphate attack concrete through an expedited testing technique. A chemical reaction over the concrete occurs during immersion, lowering the specimen weight. This weight differential indicates the impact of sulphate attack on the specimen. This investigation uses the three trial mix specimens for the test. The samples are removed from the acid in which they had been submerged and allowed to air dry for a while. The specimen is subsequently weighed using a weight balance to ascertain its ultimate weight. The results are reported in Table 6, demonstrating an average weight difference between the 2.5% and 5% trial mixes and standard concrete.

6.2. Rapid Chloride Penetration Test

Rapid Chloride Penetration Test (RCPT), or ASTM C1202, is a standardized test to assess the concrete's permeability and resistance to chloride ion penetration. Concrete specimens with dimensions of 100 mm in diameter and 50 mm in height are prepared and cured for a predetermined period of 28 days in a controlled environment.

The concrete sample is sandwiched between two testing cell halves to prevent direct contact between the concrete specimen and the chloride solution, forming an electrical circuit. A power source and a controller that monitors the electric current's movement are attached to the testing cell. The specimen is exposed to a continuous voltage. The supplied voltage causes chloride ions to move through the concrete material. The controller keeps track of the charge that flows through the specimen during a predetermined time, usually 6 hours. The total charge that passes through the sample is represented in coulombs (Coulombs). Usually, the outcome is stated as "Coulombs Passed" or "Chloride Ion Penetration Resistance".

Lower Coulombs Passed values represent more outstanding durability and resistance to chloride ion penetration, respectively. Based on the results of the test, concrete is rated as having "High," "Moderate," or "Low" chloride ion penetration resistance. According to the charge passed, Table 9 shows the chloride ion penetrability, and Table 10 lists the outcomes of the tests performed on the concrete specimens.

Table 9. Chloride penetration based on passing charges

Charge Passed in Coulomb	Value of Chloride ion Penetrability
Greater than 4000	Penetration is High
Between 2000 – 4000	Penetration is Moderate
Between 1000 – 2000	Penetration is Low
Between 100 – 1000	Penetration is Very Low
Less than 100	Negligible

The ASTM C 1202's trapezoidal rule can convert the total charge passed during this time into coulombs. The formula for the average current across one cell is $I = 900 * 2(I_{CUMMULATIVE})$ coulombs.

Where, $I_{CUMMULATIVE} = [(I_0+I_{360})/2]+[I_{30} + I_{60} + I_{90} + I_{120} + I_{150} + I_{180} + I_{210} + I_{240} + I_{270} + I_{300} + I_{330}]$

I = charge passed in coulombs

I_0 = current at zero voltage in amperes

I_t = amperes of current at time 't' minutes after the voltage is applied. The Table 9 and Figure 4 show that 2.5% phosphogypsum and alcofine added to cement increases its resistance to chloride ion penetration. Adding 2.5% of PG and AC increased the penetration of chloride ions. Therefore, it is clear that adding 2.5% more PG & AC to concrete increases the material's resistance to chloride ion penetration and places it in the deficient and negligible category in table 9's classification system.

Table 10. RCPT values of concrete specimens

Tested Specimens Based on the Percentage of Materials Replaced for Cement	RCPT Value in Coulombs		
	28 Days	56 Days	90 Days
FA – 27.5%, SF – 2.5%, PG – 0%, AC – 0%	108	123	82
FA – 22.5%, SF – 2.5%, PG – 2.5%, AC – 2.5%	98	85	55
FA – 17.5%, SF – 2.5%, PG – 5%, AC – 5%	136	258	137

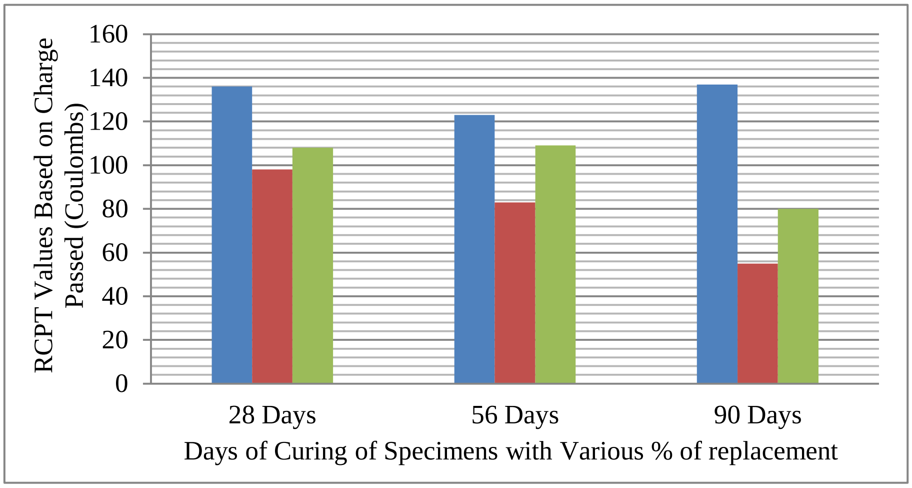

Fig. 4 RCPT values

6.3. SEM Analysis

To describe the microstructure of High-Strength Self-Compacting Concrete (HSSCC), Scanning Electron Microscopy (SEM) investigation is a valuable technique. Using this method, you can thoroughly inspect the concrete's surface morphology, mineral makeup, and microstructural characteristics. Below is an image showing how the hydration product forms and is distributed throughout different quantities of cement paste. After 28 days, the strength of the concrete was evaluated based on the increase of the hydration products. Signal collection from field emission and sample interactions is essential to create images during the SEM examination.

In SEM, a focused beam of quickly moving, high-energy particles is directed at the surface of the substrate material. The interaction between the material surface and the emitted beam reveals critical aspects, such as material surface topography, chemical properties, crystalline nature, and constituent homogeneity.

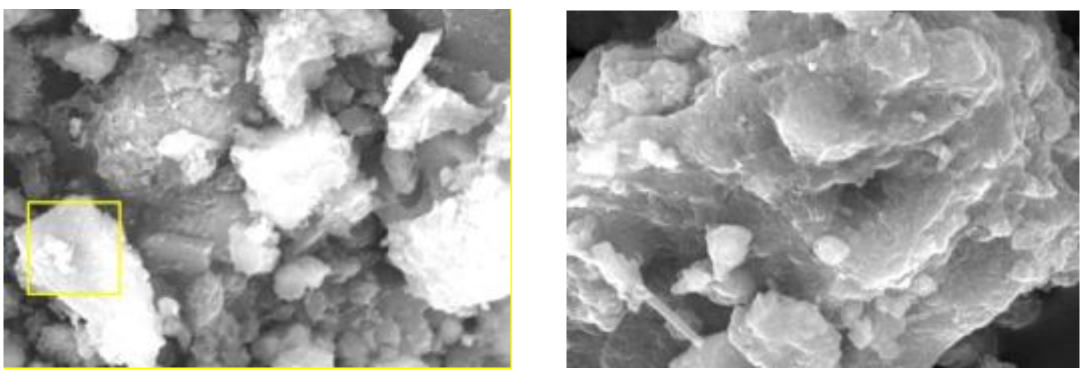

Fig. 5 SEM image of mix 1

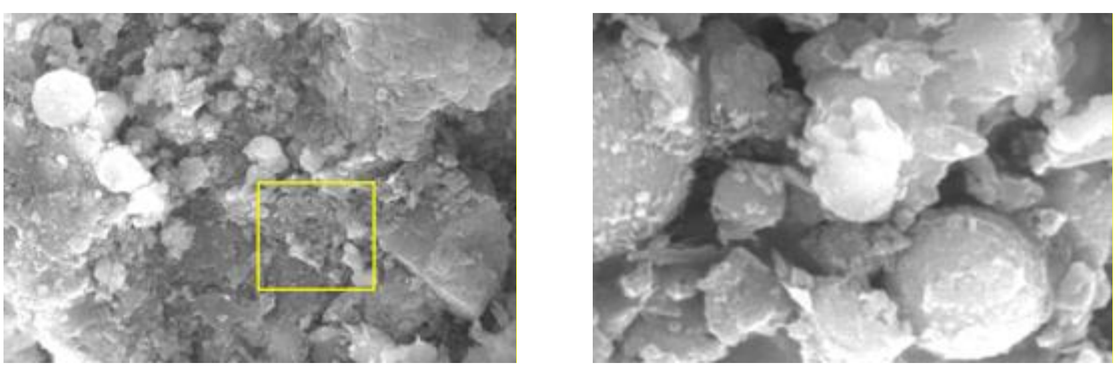

Fig. 6 SEM image of mix 2

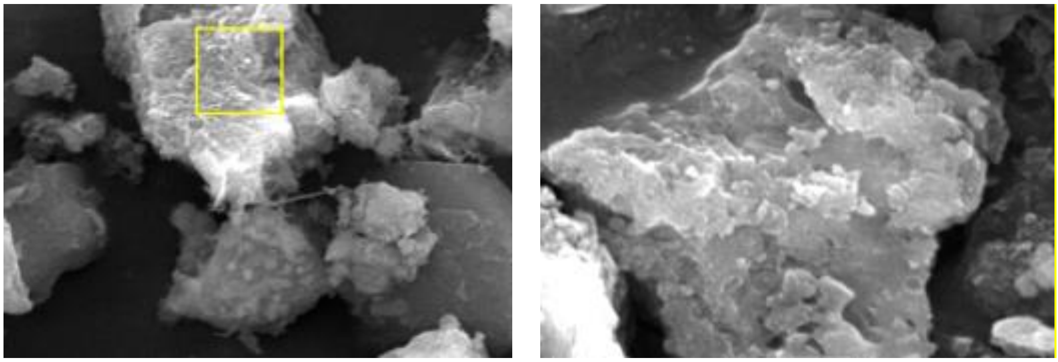

Fig. 7 SEM image of mix 3

Since the mix-1 is a standard, no admixtures are added to the concrete. Figure 5 demonstrates how more C-S-H gels have developed, giving the concrete its full strength after 28 days. After adding 2.5% alccofine and phosphogypsum, each with 2.5% silica fume and 22.5% fly ash, the SEM analysis image of mix-2, in which the C-S-H gel formation was pretty good, is displayed in Figure 6.

Due to the extensive distribution of gel in the SEM graph, the strength of the concrete with admixtures was significantly improved. Figure 7 demonstrates that the increase in the proportion of admixtures-likely 2.5% silica fume, 5% phosphogypsum and alccofine, and 17.5% fly ash (mix-3), made the C-S-H gel formation insufficient to create strength in the concrete. As a result, the concrete power is significantly lower than mix-2. Finally, it is depicted that mix 2 (2.5% of AC & PG each + 2.5% of SF + 22.5% of FA) exhibits more particle distribution than the other mixes.

7. Conclusion

As a result, a substantial advancement in concrete technology has been made with enhancing characteristics in High-Strength Self-Compacting Concrete (HSSCC) with the insertion of nano-mineral admixtures as a cement replacement. By utilizing the advantages of nanotechnology to increase SCC's performance, this novel strategy offers several improved features essential for contemporary building techniques. Using nanoscale mineral admixtures, like flyash, silica fume, phosphogypsum and alccofine, has several significant benefits. Increasing mechanical strength, mainly compressive and flexural strength, makes building more durable and resilient structures possible—this increase in strength benefits SCC's structural integrity, overall durability, and load-bearing capacity.

As 2.5% of replacement, the nano mineral admixtures improve results in all areas, such as mechanical characteristics (compressive strength, split tensile strength, and flexural strength) and durability properties (alkali resistance, chloride ion penetration, resistance and SEM analysis).

The power decreases in all respects if the admixture amount goes from 2.5% to 5%. So, it is clear that between 2.5% and 5% is the sweet spot for admixture replacement. Additionally, using nano mineral admixtures helps reduce the water-to-binder ratio, essential for strengthening concrete's durability and lowering the risk of sulphate attack and the Alkali-Silica Reaction (ASR). In a time when sustainability is a top priority, adding nano mineral admixtures to SCC is in keeping with the values of environmental friendliness. The lower cement concentration reduces the carbon footprint of making concrete while preserving priceless natural resources.

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