IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Nano-Silica Modified Self-Healing Concrete

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Abstract: Nano-silica-modified self-healing concrete represents an approach to enhancing concrete durability and sustainability by integrating Nano-scale materials with self-healing properties. Nano-silica, due to its high surface area and reactivity, not only improves concrete's mechanical strength and microstructural density but also amplifies its self-healing capabilities. In self-healing concrete, cracks that develop over time can autonomously close, largely through a combination of ongoing hydration reactions and precipitation of calcium carbonate in the crack voids. Nano-silica accelerates the formation of calcium silicate hydrate (C-S-H) by reacting with calcium hydroxide (CH), filling voids and micro-cracks effectively. This densification reduces permeability, improves crack resistance, and creates a more robust environment for the natural self-healing process. Enhanced by Nano-silica's pozzolanic reaction, the healing capacity of concrete is significantly boosted, particularly in smaller cracks that would otherwise go untreated. Additionally, nano-silica's ability to reduce cement content contributes to sustainability by lowering the carbon footprint associated with cement production. The synergy between nano-silica and self-healing mechanisms presents a promising material solution for extending the lifespan and reducing maintenance costs of concrete structures, making it ideal for infrastructure exposed to harsh environmental conditions.

I. INTRODUCTION

The construction industry is indeed undergoing a transformative shift toward sustainability and innovation. Self-healing concrete is a remarkable advancement that addresses both durability and environmental concerns. By incorporating specialized materials, this concrete can autonomously repair cracks, which not only extends the lifespan of structures but also reduces maintenance costs and resource consumption.

Nano-silica modified self-healing concrete takes this a step further. The addition of Nano-silica enhances the mechanical properties of the concrete, improving strength and durability while also facilitating the self-healing process. This combination makes it an attractive option for infrastructure development, as it aligns with the growing emphasis on sustainable building `practices.

II. MATERIALS AND METHODS

Cement

Cement is a key construction material that acts as a binding agent in concrete and mortar, essential for infrastructure like buildings, roads, and bridges. It is primarily made of lime, silica, alumina, and iron oxide, with gypsum added to regulate setting time. The most common type is Ordinary Portland Cement (OPC), though other types like Portland Pozzolana Cement (PPC) cater to specific needs. Cement undergoes a hydration process with water, forming compounds that provide strength and durability. Known for its versatility, high compressive strength, and resistance to weathering, cement is indispensable in modern construction and continue to evolve with innovations for sustainability and enhanced performance.

Fine Aggregete

Fine aggregate consists of small particles like natural sand, crushed stone, or manufactured sand (M-sand) with sizes ranging from 0.075 mm to 4.75 mm. It fills the voids between coarse aggregates, enhancing the mix's density, strength, and workability. Proper fine aggregate should be clean, well-graded, and free from impurities like silt and organic matter. It plays a crucial role in improving the durability, strength, and overall quality of construction materials.

Coarse Aggregate

Coarse aggregate is a vital component of concrete, consisting of larger particles such as crushed stone, gravel, or recycled concrete with sizes typically ranging from 4.75 mm to 80 mm. It provides bulk, strength, and stability to the concrete mix, forming the skeleton of the structure. Properly graded and clean coarse aggregates improve the durability, load-bearing capacity, and resistance to wear and weathering, making them essential for strong and long-lasting construction.

Table I. Material Test Results

MATERIALS	TESTS	RESULTS
Cement	Standard consistency test as per IS: 4031	32%
	Initial setting time as per IS 4031, IS 269	31min
	Specific Gravity as per IS 2720- Part 3	2.8
Fine Aggregate	Sieve Analysis as per IS: 2386(Part - I)-1963	Conforming to grading Zone II of Table 7 of IS 383
	Water Absorption as per IS: 2386(Part - III)-1963	1%
	Specific Gravity as per IS: 2386(Part - III)-1963	2.65
Coarse Aggregate	Sieve Analysis as per IS: 2386(Part - I)-1963	Conforming to table 7 of IS 383
	Water Absorption as per IS: 2386(Part - III)-1963	0.5%
	Specific Gravity as per IS: 2386(Part - III)-1963	2.74

Nano-silica

Nano-silica, also known as silica nanoparticles, is a highly reactive material consisting of particles ranging from 1 to 100 nanometers (nm) in size, with an average size of 10-20 nm. Characterized by its high surface area (typically 100-500 m^2/g) and pozzolanic properties, Nano-silica reacts with calcium hydroxide to form calcium silicate hydrate, significantly enhancing the performance of cement concrete, improving the microstructure by filling voids, reducing porosity, and promoting the formation of additional calcium silicate hydrate (C-S-H) gel. When added to concrete, Nano-silica increases compressive strength, durability, and resistance to environmental factors like chemical attack and water permeability. It is typically used in small amounts, ranging from 1% to 3% by weight of cement, to achieve superior concrete performance.

Slump Test

The slump test is a widely used method as per IS: 1199-1959 to assess the workability or consistency of fresh concrete. It involves filling a cone-shaped mold with concrete, removing the mold, and measuring the vertical settlement of the concrete, known as the slump value. The slump indicates the flowability of the concrete: very low (0-25 mm) for stiff mixes like road pavements, low (25-75 mm) for lightly reinforced foundations, medium (75-150 mm) for general construction, and high (150-175 mm) for highly flowable concrete used in heavily reinforced structures. This test ensures the mix meets workability requirements for specific applications.

Bacteria

Bacillus subtilis, a type of bacteria, has been increasingly used in concrete to enhance its durability and sustainability. When added to concrete, Bacillus subtilis produces calcite, a natural cementitious material, through a process called microbially induced calcite precipitation (MICP). This calcite precipitation fills in the pores and cracks in the concrete, improving its strength, density, and resistance to degradation. The bacteria also produce biofilms that act as a protective barrier, reducing the penetration of harmful substances and increasing the concrete's self-healing capabilities. Furthermore, Bacillus subtilis is a non-pathogenic and environmentally friendly bacteria, making it an attractive alternative to traditional chemical-based concrete admixtures. The use of Bacillus subtilis in concrete has shown promising results in improving the durability and sustainability of concrete structures, and its potential applications range from construction to repair and retrofitting of existing infrastructure.

III. OPTIMUM PERCENTAGE OF NANO-SILICA

The optimum dosage of Nano-silica in M40 grade concrete typically ranges from 1% to 3% by weight of cement, depending on factors such as dispersion method, cement type, and desired properties.

Working principle

The incorporation of Nano-silica (NS) in cement concrete significantly enhances its properties through distinct physical and chemical effects. Physically, NS particles fill the voids between cement grains, effectively reducing porosity and improving density. This optimized particle packing also enhances particle distribution, reducing spacing and increasing paste thickness, resulting in a more homogeneous and denser matrix. Chemically, NS undergoes a pozzolanic reaction with calcium hydroxide (CH) to form calcium-silicate-hydrate (C-S-H) gel, the primary binding phase responsible for cement's strength. Additionally, NS accelerates cement hydration, facilitating the formation of C-S-H gel and thereby improving early-age strength. These synergistic effects contribute to enhanced mechanical properties, improved durability, and reduced permeability, making NS an effective additive for high-performance concrete applications.

IV. MIX DESIGN

As per IS 10262:2019 and IS 456:2000 guidelines, the mix design of M40 concrete with Nano-silica aims to enhance strength and durability by incorporating Nano-silica particles, which improve the microstructure of the concrete. The typical water-cement ratio is 0.38 and cement: fine aggregate: coarse aggregate proportions of 1:1.5:2.7 by weight. Nano-silica is added according to optimum percentage obtained is 3%, which is to enhance the hydration process, leading to improved compressive strength and reduced permeability. The slump value is typically maintained between 75-125 mm. Trial mixes and compressive strength tests at 7, 14, and 28 days ensure the mix achieves the desired performance for high-strength, durable concrete in applications like high-rise buildings and bridges.

Preparation of samples

The concrete samples were prepared according to the IS: 10262-2019. Different moulds are prepared for evaluating the strength and durability characteristics of concrete. Cubical specimens of size 150 x 150 x 150 mm are cast for compressive strength test and water absorption test, cylindrical specimens of size 150 x 300 mm are prepared for split tensile strength test, and Beam specimens of size 100 x 100 x 500 mm are cast for flexural strength test and acid attack test. The moulds are fixed tightly and coated with oil and concrete is poured in three layers of each mould. The Nano-silica was applied to the concrete by the direct application method . The tamping was done with a rod of the rounded end for 25 times, which distributed concrete and Nano-silica equally in the mould. The specimens are demoulded after 24hrs and cured for 7, 14 and 28 days. The three specimens of each are taken as an average for evaluating the test results.

Working principle

Concrete with the addition of Nano-silica particles (typically 3% by weight of cement) to enhance the hydration process and improve the microstructure of the concrete. When mixed, the Nano-silica particles fill the micro-voids in the concrete, reducing porosity and increasing the density of the concrete. This results in higher compressive strength and durability. Nano-silica also promotes the formation of additional calcium silicate hydrate (C-S-H) gel, which further strengthens the matrix and improves the bond between cement and aggregates. As a Result , the concrete gains improved mechanical properties, resistance to chemical attacks, and reduced permeability, making it suitable for high-performance applications. The mix also requires a low water-cement ratio (around 0.38), and a superplasticizer is used to maintain workability despite the reduced water content.

V. MECHANICAL TEST

Compression Test

A compression test (IS: 10086-1982) is a mechanical evaluation used to assess a material's behavior under compressive force. Cubes of size 15cm x 15cm x 15cm (IS: 10086-1982) were casted. All the specimens were provided with adequate time for hardening and cured for 7, 14 and 28 days. After the enumerated period (7, 14 and 28 days) all the specimens were examined for its maximum load in the compression testing machine. The compressive strength of concrete for specimens with optimum content of Nano-silica at 7 days, 14 days and 28 days is given. It was observed that the compressive strength of Nano-silica added concrete showed a serious increase than conventional concrete.

Table II. Compressive test results

Percentage of Nano-silica	Compressive Strength at 7 days (MPa)	Compressive Strength at 14 days (MPa)	Compressive Strength at 28 days (MPa)
1%	30.53	32.6	37.7
2%	32.2	34.5	41.37
3%	34.98	39.69	45.4
4%	33.65	35.8	42.2

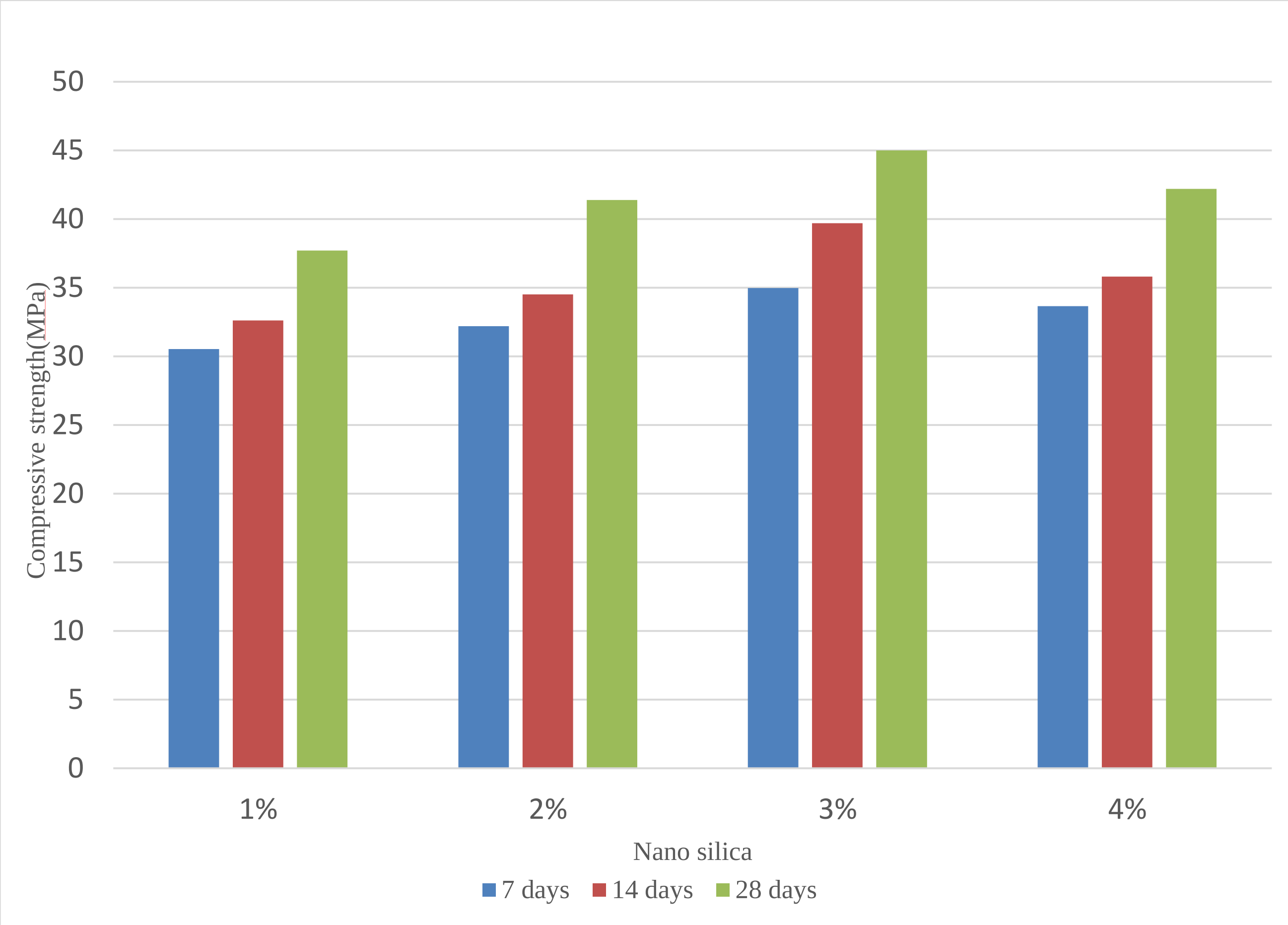

fig i. compressive strength result

VI. RESULT OF STRENGTH AND DURABILITY TEST ON NANO SILICA MODIFIED SELF HEALING CONCRETE

Compressive strength test

The compressive strength depends on the amount of calcium carbonate produced . Cubes of size 15cm x 15cm x 15cm (IS: 10086-1982) were casted in the present study. All the specimens were provided with sufficient time for hardening and cured for 7, 14 and 28 days. After the specified period (7, 14 and 28 days) all the specimens were tested for its maximum load in the compression testing machine. The compressive strength of concrete for specimens with nano silica concentration of 3 % at 7 day, 14 day and 28 day are taken . It was observed that the compressive strength of nano silica modified concrete showed significant increase than conventional concrete.

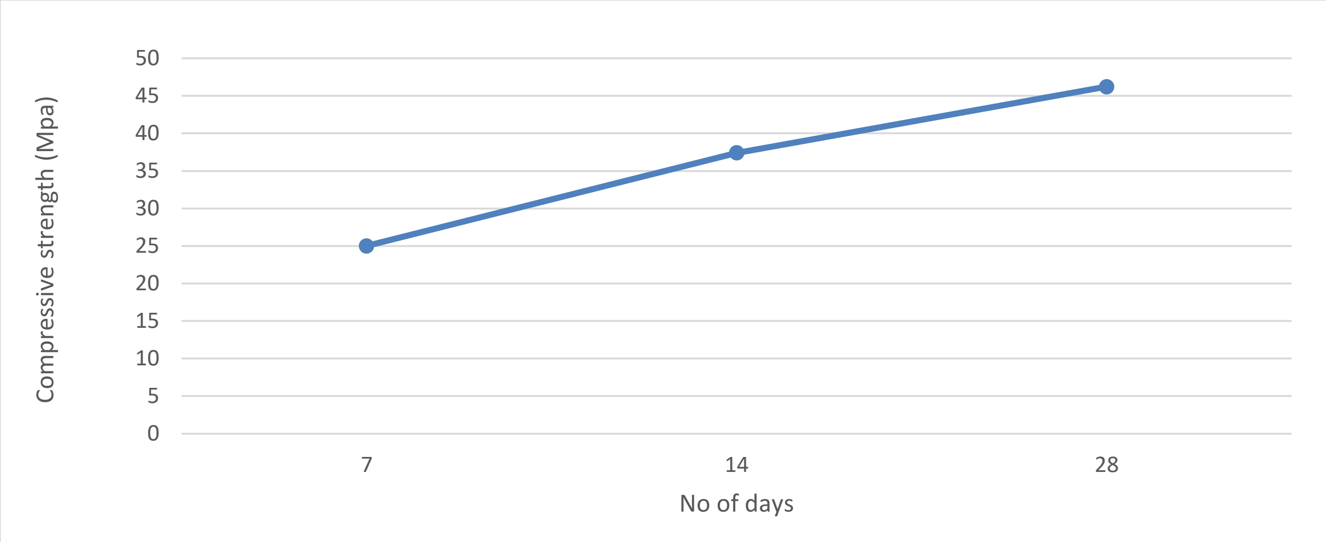

fig ii. 7day,14day and 28day compressive strength

Split tensile strength test

The Split Tensile Strength on standard cylindrical specimens of size 150mm diameter and 300mm long were casted with nano silica concentration of 3% at 7 day, 14 day and 28 day are taken. After 24 hours the specimens were demoulded and subjected to water curing. After 7, 14 and 28 days of curing the cylinders were taken allowed to dry and tested in compression testing machine by placing the specimen horizontal. It was observed that with the addition of nano silica , there is a significant increase in the tensile strength

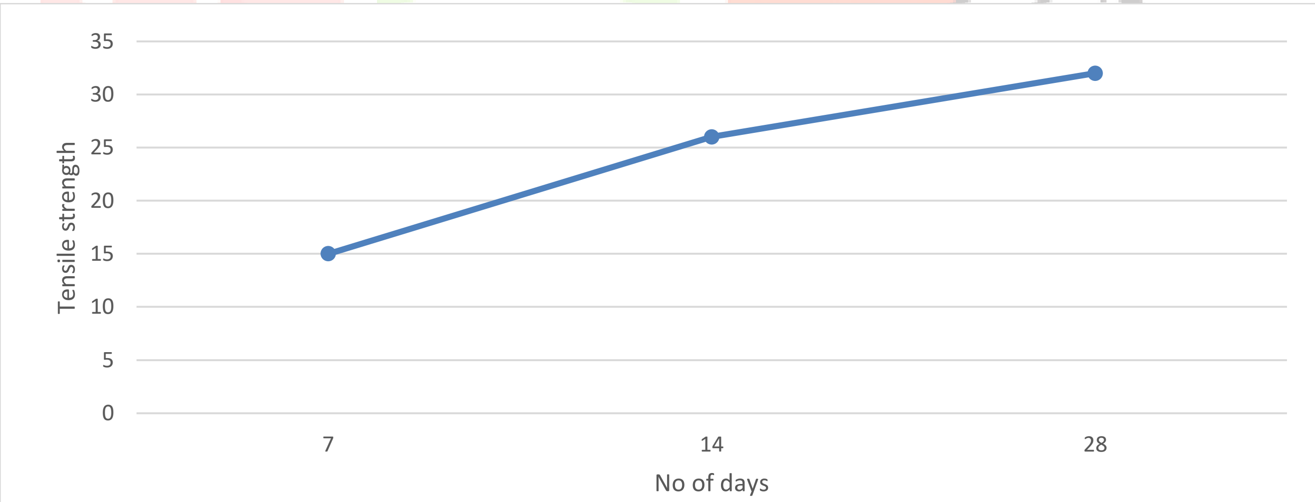

fig iii. 7day,14day and 28day tensile strength

Flexural strength test

The flexural Strength on standard beam specimens with different bacterial concentration at 7 day, 14 day and 28 day are taken. The increase in strength of nano silica concrete is mainly due to filling of the pores and voids with microbiologically induced calcium carbonate precipitation. It was observed that with the addition of nano silica , there is a significant increase in the tensile strength.

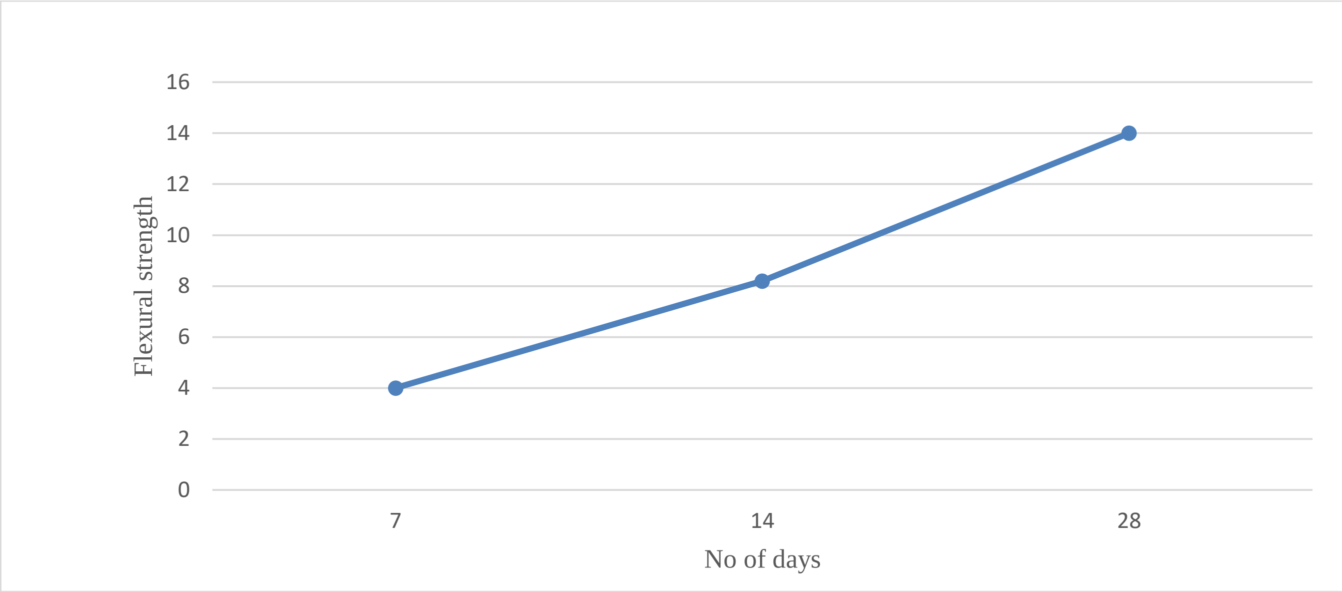

fig iv. 7day,14day and 28day flexural strength

Water absorption test

This test is likewise emphatically influenced by the dampness state of the solid at the season of testing including the length of introduction and temperature. The water absorption of bacterial concrete has lower rate compared to conventional concrete, this is because of the microorganisms actuated development of calcium carbonate in the voids in concrete, leading to a lesser void and hence a lesser permeability. Addition of bacterial causes reduction in water absorption and porosity which could in turn increase durability of concrete structures. The reducing water absorption was because of the effectiveness of bacteria in depositing layers of calcium carbonate into the cavities, pores and micro-cracks of concrete specimens that seal pores and micro cracks.

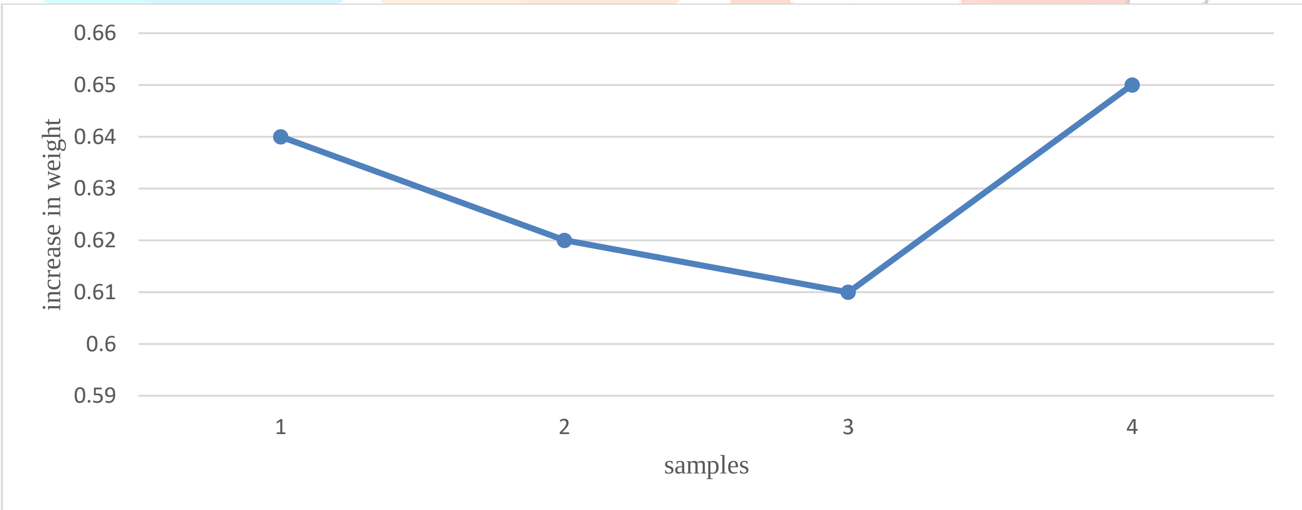

fig v. water absorption test

Carbonation test

The carbonation test analysis involves evaluating parameters such as carbonation depth, carbonation rate, and carbonation front to assess the concrete's resistance to carbonation and potential for corrosion. A low carbonation depth indicates good resistance and low corrosion risk, while a high carbonation depth suggests poor resistance and high corrosion risk. The carbonation rate also provides valuable insights, with a high rate indicating a higher corrosion risk. However, factors such as concrete mix design, environmental conditions, and curing conditions can influence the test results, and limitations including accelerated testing, variability, and interpretation challenges must be considered when evaluating the data.

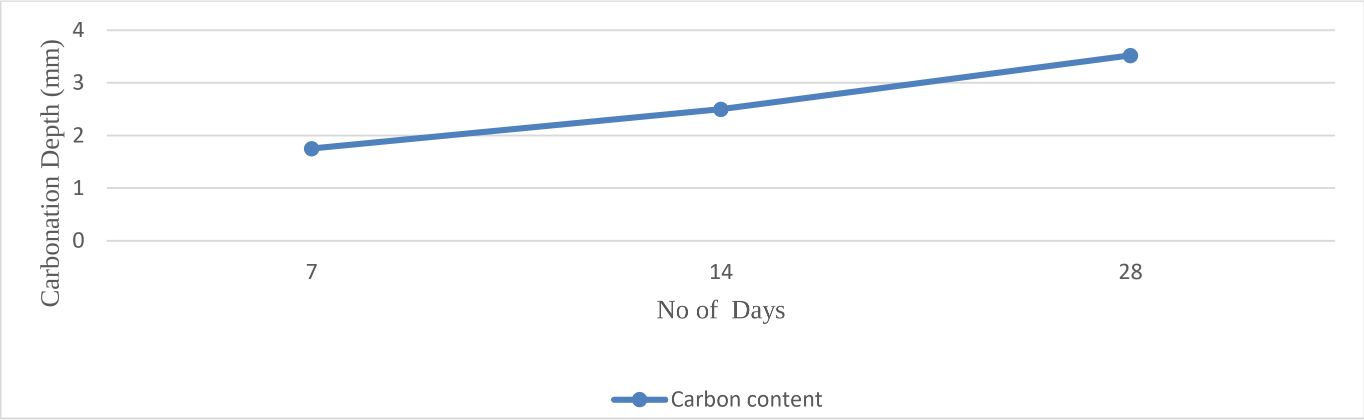

fig vi. carbonation test

Self healing of cracks

The self-healing process using Bacillus subtilis involves the bacteria producing enzymes that break down urea, releasing ammonia and carbon dioxide. These react with calcium ions to form calcite, which precipitates and fills cracks in the concrete, restoring its strength and ImageJ software is used to analyze the self-healing process of Bacillus subtilis, by measuring the crack width and gives the percentage decrease in crack width. It measures crack width, calculates crack closure percentage by this analyzes and evaluates self-healing effectiveness.

Days	Initial Crack Width(mm)	Reduced Crack Width(mm)	Percentage decrease(%)
7	0.5	0.3	40
14	0.5	0.2	60
28	0.5	0.1	80

CONCLUSION

From the experimental work carried out , the incorporation of nano silica into self-healing concrete has proven to be a highly effective approach in enhancing the mechanical and durability properties of concrete. The nano silica modified self-healing concrete exhibits significantly higher strength and durability compared to conventional concrete, making it an ideal material for sustainable and durable construction. The improved performance of nano silica modified self-healing concrete can be attributed to the enhanced reactivity, pozzolanic activity, and self-healing capabilities provided by the nano silica. With its superior strength, durability, and self-healing properties, nano silica modified self-healing concrete is poised to revolutionize the construction industry, enabling the creation of more sustainable, resilient, and long-lasting infrastructure.

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