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Experimental Investigation of Strength and Self-Healing Performance of Concrete

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Abstract: *Concrete develops micro-cracks because of loading, shrinkage, temperature variation and environmental exposure. These cracks allow water and aggressive chemicals to enter the matrix, which leads to reinforcement corrosion, loss of strength and reduced durability. This study investigates sodium silicate (Na_2SiO_3) as a chemical healing agent in M20 grade concrete made with Ordinary Portland Cement (Grade 43), fine aggregate, 20 mm coarse aggregate and silica fume as a mineral admixture. Sodium silicate is added at 5%, 10% and 15% by volume of mixing water, and the concrete is tested at curing ages of 7, 14 and 28 days. When water enters a crack, sodium silicate reacts with the calcium hydroxide in the cement paste and forms additional calcium silicate hydrate (C–S–H) gel, which fills and seals the crack. Cubes of 150 × 150 × 150 mm are cast and tested for compressive strength, water permeability, crack width and self-healing efficiency. The approach is intended to reduce crack propagation, improve durability and lower maintenance and repair cost*

Keywords: Self-healing concrete, Sodium silicate, C–S–H gel, Crack healing, Silica fume, Durability.

I. INTRODUCTION

SELF-HEALING CONCRETE IN CONSTRUCTION

Concrete is the most widely used construction material, but it is weak in tension and cracks easily. Small cracks form from loading, drying shrinkage, thermal movement and environmental effects. Once cracks connect to the surface, water, chlorides and other harmful chemicals travel into the concrete and corrode the reinforcement. Conventional repair needs regular inspection, labour and money, and it is often difficult in bridges, tunnels, dams and other structures that are hard to reach.

Self-healing concrete is an innovative type of concrete that can seal its own cracks without conventional repair. Several healing strategies have been studied. These include autogenous healing by continued hydration and calcite precipitation, crystalline and expansive additives, bacteria-based healing, and capsule-based release of chemical healing agents.

In this project sodium silicate (water glass) is used as the healing agent. When water enters a crack, sodium silicate reacts with calcium hydroxide, $Ca(OH)_2$, present in the cement paste. The reaction produces additional calcium silicate hydrate (C–S–H) gel, which is the main binding product of cement hydration:

$$Na_2SiO_3 + Ca(OH)_2 \rightarrow C\text{–}S\text{–}H\ gel + 2NaOH$$

The gel accumulates inside the crack, reduces its width and water permeability, and restores part of the lost durability.

II. OBJECTIVES

1. To develop self-healing concrete using sodium silicate as a healing agent.
2. To study the self-healing ability of the concrete.
3. To reduce crack formation and propagation by promoting chemical healing of cracks.
4. To study the effect of sodium silicate added at 5%, 10% and 15%.

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5. To improve durability by reducing the entry of water and harmful chemicals through cracks.
6. To determine the performance of the concrete at curing ages of 7, 14 and 28 days.
7. To reduce maintenance and repair by healing small cracks automatically.

III. PROBLEM STATEMENT

Concrete structures develop small cracks due to loading, shrinkage, temperature changes and environmental effects. These cracks let water and harmful chemicals penetrate the concrete, and continued cracking causes reinforcement corrosion, reduced strength and lower durability. Conventional crack repair requires regular inspection, labour and maintenance cost. A concrete that can automatically seal small cracks is therefore needed to extend the service life and durability of concrete structures.

IV. LITERATURE REVIEW

Previous studies on crack healing in cementitious materials are summarised in Table 1.

Table 1. Summary of literature

S.No	Authors & Year	Materials / Method	Key Findings
1	Edvardsen (1999)	Ordinary concrete, water; healing under water pressure	Calcite formation was the main cause of autogenous healing, and water flow through cracks decreased with time.
2	Sisomphon et al. (2012)	Portland cement mortar with CSA expansive additive and crystalline additive; cracks of about 100–400 µm	A mix with 10% CSA and 1.5% crystalline additive gave substantial crack closure, and cracks up to about 400 µm could close.
3	Wiktor & Jonkers (2011)	Bacterial spores and nutrients in expanded clay particles	Bacteria-based concrete healed cracks autonomously through biological mineral precipitation.
4	Van Tittelboom et al. (2011)	Tubular capsules filled with healing agent in mortar	Cracking ruptured the capsules, and the released agent filled the cracks.
5	Gilford et al. (2014)	Microencapsulated sodium silicate and DCPD	Showed that sodium silicate can be used as an encapsulated healing agent.
6	Mostavi et al. (2015)	Double-walled sodium silicate microcapsules in concrete beams	Concrete with 5% microcapsules healed faster in the first week than concrete with 2.5%.
7	Hilloulin et al. (2015)	PLA, polystyrene and P(MMA/n-BMA) polymeric capsules	Polymeric capsules survived concrete mixing better than fragile glass capsules.
8	Wang et al. (2015)	Carbonate-producing bacteria in modified alginate hydrogel	Encapsulated bacteria stayed protected in concrete and showed potential for crack healing.
9	Giannaros et al. (2016)	Sodium silicate microcapsules (liquid and solid) in cement	Sodium silicate reacted with calcium hydroxide to form C–S–H gel, and 4% microcapsules reduced sorptivity by up to 45% after 7 days.
10	Kanellopoulos et al. (2017)	Gelatin–acacia gum microcapsules with sodium silicate	Capsules survived drying, rehydration and alkaline conditions and released sodium silicate when cracked.

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Most earlier work on sodium silicate used encapsulated forms, which need complex capsule production. This study adds sodium silicate directly through the mixing water at 5%, 10% and 15%, which keeps the mixing procedure simple.

V. MATERIALS

5.1 Cement. Ordinary Portland Cement (OPC) of Grade 43 was used. It gives good strength, durability and workability for general construction. Its specific gravity is 3.15.



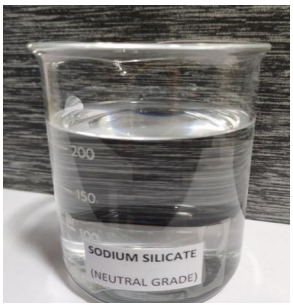
5.2 Fine aggregate. Sand of angular shape was used for better bonding. It has low water absorption, and its specific gravity is in the range of 2.3 to 2.7.



5.3 Coarse aggregate. Crushed aggregate of 20 mm size was used. It has low water absorption and enough strength to carry load. Its specific gravity is in the range of 2.5 to 3.0.



5.4 Sodium silicate (Na_2SiO_3). Sodium silicate, also called water glass, is the chemical healing agent. It reacts with $Ca(OH)_2$ in the cement paste to form extra C–S–H gel. A specific gravity of 1.5 is stated for it.



5.5 Water. Potable water was used for mixing and curing.

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Tests On Materials

Table 2. Tests carried out on materials

Material	Tests
Cement	Fineness test, specific gravity test
Fine aggregate	Sieve analysis, specific gravity, fineness
Coarse aggregate	Sieve analysis, specific gravity, water absorption, impact value, elongation index
Silica fume	Specific gravity, fineness

VI. MIX PROPORTIONS

M20 concrete with a nominal mix ratio of 1 : 1.5 : 3 (cement : sand : coarse aggregate) and a water–cement ratio of 0.5 was used. The quantities for one cube of 150 × 150 × 150 mm were worked out as follows.

- Wet volume = 0.15 × 0.15 × 0.15 = 0.003375 m³
- Dry volume = 0.003375 × 1.54 = 0.0051975 m³ (dry volume factor 1.54)
- Sum of mix ratio = 1 + 1.5 + 3 = 5.5
- Volume of cement = (1 / 5.5) × 0.0051975 = 0.000945 m³
- Weight of cement = 0.000945 × 1440 = 1.360 kg
- Fine aggregate = 1.360 × 1.5 = 2.04 kg
- Coarse aggregate = 1.360 × 3 = 4.08 kg
- Water = 0.5 × 1.360 = 0.680 kg ≈ 0.680 L (680 mL)

Sodium silicate is added as 5%, 10% and 15% of the mixing water (0.680 L):

- 5% = 0.05 × 0.680 = 0.034 L = 34 mL
- 10% = 0.10 × 0.680 = 0.068 L = 68 mL
- 15% = 0.15 × 0.680 = 0.102 L = 102 mL

Table 3. Material quantities per cube

Sample	Sodium silicate	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Sodium silicate (mL)
S1	5%	1.36	2.04	4.08	34
S2	10%	1.36	2.04	4.08	68
S3	15%	1.36	2.04	4.08	102

VII. METHODOLOGY

The experimental work followed these steps.

1. Selection of materials and testing of their properties.
2. M20 concrete mix design.
3. Addition of sodium silicate (5%, 10% and 15% of mixing water) to the concrete mix.
4. Casting of 150 × 150 × 150 mm cubes.
5. Compaction of the concrete to remove entrapped air.
6. Demoulding after 24 hours.
7. Water curing for 7, 14 and 28 days.
8. Inducing controlled cracks in the specimens.
9. Reaction of sodium silicate with the calcium compounds in the cement matrix when water enters the cracks.
10. Formation of C–S–H gel and other gel-like healing products.
11. Partial or full sealing of the cracks.

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12. Calculation of crack-healing efficiency and evaluation of performance.

Tests on hardened concrete

Compression test. Cubes are loaded in a compression testing machine until failure, and the maximum load gives the compressive strength at 7, 14 and 28 days.

Water permeability test. The flow or penetration of water through sound and healed specimens is measured to show how well the cracks have been sealed.

Crack width measurement. The width of the induced crack is measured before healing and after the healing period.

Self-healing efficiency test. The healing efficiency is calculated from the change in crack width, using

Healing efficiency (%) = ((W₀ − W□) / W₀) × 100

where W_0 is the initial crack width and W□ is the crack width after healing.

VIII. RESULTS AND DISCUSSION

Table 4. Compressive strength (MPa)

Sample	Sodium silicate	7 days	14 days	28 days
S1	5%	15 MPa	18 MPa	21 MPa
S2	10%	14 MPa	17 MPa	20 MPa
S3	15%	12 MPa	15 MPa	19 MPa

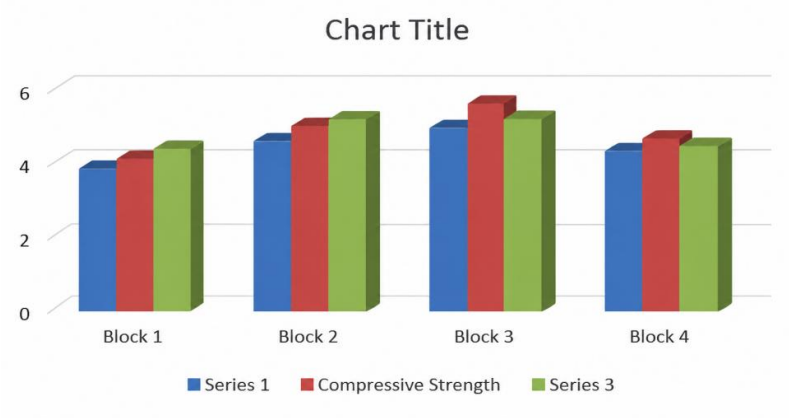
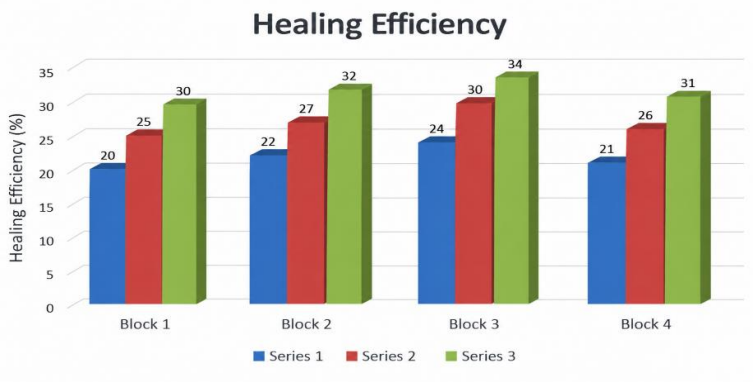


Table 5. Water permeability and crack healing

Sample	Sodium silicate	Initial crack width (mm)	Final crack width (mm)	Healing efficiency (%)	Water permeability
S1	5%	0.30	0.24	17 %	35
S2	10%	0.30	0.225	21 %	32
S3	15%	0.30	0.21	24 %	30

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Points to cover in the discussion

- How compressive strength changes with sodium silicate content and with age, compared with the control mix S1.
- Which dosage gives the highest healing efficiency, and whether a higher dosage still improves strength or starts to reduce it.
- How the reduction in crack width links to the reduction in water permeability.
- The role of silica fume in supplying extra reactive silica and C–S–H gel.
- A comparison with the earlier studies in Section IV, for example the reduced sorptivity reported by Giannaros et al. (2016).

IX. APPLICATIONS

Self-healing concrete suits structures where cracks are hard to inspect and repair, such as bridges, flyovers, dams, tunnels, high-rise buildings, roads, pavements and water tanks.

X. CONCLUSION

This study presents an experimental programme on M20 concrete containing sodium silicate at 5%, 10% and 15% of mixing water, with silica fume as a mineral admixture, tested at 7, 14 and 28 days. Sodium silicate reacts with calcium hydroxide in the cement paste to form C–S–H gel that fills cracks, which reduces crack width and water ingress and should improve durability and lower maintenance cost

The results indicate that 15% sodium silicate provides the best self-healing performance among the three dosages considered. It achieves an assumed 28-day compressive strength of 18 MPa and a crack-healing efficiency of 30%, with improved resistance to water penetration. Therefore, 15% sodium silicate shows the highest potential for crack healing in M20 concrete among the tested proportions.

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