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Study of the effect of Silica fume on the Self-healing ability of High Strength Concrete with Crystalline Admixture

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Abstract—*The aim of this study is analyzing the self-healing capability of High strength concrete (M70) with Silica fume and Crystalline admixture in four types of environmental exposures i.e. Water Immersion, Wet/Dry Cycles, Water contact and Air Exposure. The percentage replacement of cement with silica fume were: 5%, 10%, 15% and with the addition of 1.1 % crystalline admixture .The specimens were pre-cracked at 28 days, in the range of 0.10-0.40 mm and the time set for healing was 42 days. The result shows that all the mixes have considerable amount of closing ability and strength regaining capability for all exposure conditions. The concrete with 10% Silica Fume (SF) and 1.1% Crystalline Admixture (CA) has complete crack closing ability and 100% strength regained capability for WI and W/D conditions.*

Keywords— *Crystalline Admixture, High strength Concrete, Self-healing, Silica Fume.*

I. INTRODUCTION

Cracks inevitably exist in concrete due to Chemical shrinkage, Dry shrinkage, Autogenous shrinkage, the relatively low tensile strength and so on. If micro cracks grow and reach the reinforcement, notonly the concrete itself may be attacked, butalso the reinforcing steel bars will be corroded. Therefore it is important to control the Crack width and to heal the cracks as soon as possible. Self-healing concrete also called as Self-repairing concrete, is mostly defined as the ability of concrete to repair its cracks autogenously or autonomously. Self-healing concrete can be categorised in to two types: Autogenous and Autonomous self-healing concrete. The Autogenous self-healing mainly depends on further hydration of Cement/other binders and carbonation of $Ca(OH)_2$. However, the Autonomous self-healing concrete depends on manual methods. Such as the use of Super absorbent polymers (SAP'S), Bacterial concrete, Microencapsulated healing agents, and the use of Crystalline admixtures. Crystalline admixture is a Waterproofing admixtures and it reduces the size of capillary pores, their numbers and continuity inside the concrete structure [10]. They are many products in the market now a days which are available to protect the concrete structure from damage due to water penetration. For example, Coatings, Sealers, Membranes etc. are used to prevent water penetration.

Abram's [1] was among the first researchers who explained the autogenic self-healing in concrete. He suggested that the healed strength of concrete is caused by the retarded or the interrupted hydraulicity of the cement. Edvardsen [2] conducted some experiments in order to verify the water flow in different crack width, under different pressure conditions. She found that, after 7 weeks exposure for lower pressure of the water, the cracks were closed completely whereas the same one for higher pressure had just 25% of closure. Sahraman et al. [3] investigated the recovery of compressive strength after the introduction of cracks marked by different cracking modes. In the first case, cracking is performed pre-loading specimens up to 90% of their compressive strength and after conditioning for 30 days of water curing, the strength reduction of pre-damaged specimens was only 7% with respect to virgin specimens at the same age, indicating a substantial healing. K. Sisomphon et al.[4] Studies the self-healing behaviour of Strain Hardening Cementitious Composites (SHCC) incorporating Calcium Sulphoaluminate based expansive Additive (CSA) and Crystalline Additive (CA). After 28 days curing, the specimens were pre-cracked with subsequent healing in different exposure conditions. The recovery of mechanical properties was investigated. The mixture with 10% CSA along with 1.5% CA addition showed the optimum mechanical recovery. Ferrara et al. [5] a methodology has been proposed and validated to assess and quantify the effects of self healing on the recovery of mechanical properties of normal strength concrete, with and without crystalline admixtures under different exposure conditions. M. Roig-Flores et al. [6] analyzing the self-healing effect of a crystalline admixture in four types of environmental exposure comparing with a reference concrete. The studied crack openings were under 300µm and the time set for healing was 42 days. Specimens cast with concrete containing crystalline admixtures and stored under water immersion achieved the highest self-healing rate. M. Roig-Flores et al. [7] study on the self healing capacity of early-age fiber-reinforced concrete and the effectiveness of a crystalline admixture as self healing agent in different exposure conditions. The results show the best healing exposure condition among the ones herein investigated is water immersion at 30^0 c with the crystalline admixture.

The main objective of this project is to determine the self healing ability of high strength concrete (M70) with Silica fume and Crystalline admixture in different exposure conditions.

II. EXPERIMENTAL PROGRAM AND METHODOLOGY

A. Materials and Mix Proportions

The materials used for this research were Cement, Coarse aggregate, Fine aggregate, Water, Silica Fume, Crystalline Admixture, Super plasticizer and Steel fibers.

The type of Cement was OPC 53 grade for normal concrete, concrete with silica fume, concrete with crystalline admixture and concrete with both silica fume and crystalline admixture. For better results, locally available Potable water confirming to IS 456-2000 is used for making concrete. Aggregates of size (12-10mm) were selected as Coarse aggregate, and river sand was used as fine aggregate. The quantity of Steel fibers was fixed at 40 kg/m³ according to the criterion of making the crack opening easily controllable while avoiding excessive branching of cracks. A dosage of 1.1% of crystalline admixture was introduced in the concrete by partial replacement of cement. Two types of admixtures namely, Silica fume as partial replacement of cement and Superplasticizer, for increasing workability of the fresh concrete, were incorporated in the concrete mixture. The Mix Proportions are shown in Table 1.

TABLE I
MIX PROPORTIONS OF HIGH STRENGTH CONCRETE (M70)

Mixes	Silica fume (%)	Cement (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Silica fume (kg/m³)	Water (lit/m³)	Super plastici-zer (lit/m³)	Crystalline admixture (kg/m³)	Steel fibers (kg/m³)
M1	0	494	700	1136	0	148	4.94	0	9.88
M2	5	469.3	700	1136	24.7	148	4.94	0	9.88
M3	10	445	700	1136	49.4	148	4.94	0	9.88
M4	15	420	700	1136	74.1	148	4.94	0	9.88
M5	0	494	700	1136	0	148	4.94	5.434	9.88
M6	5	469.3	700	1136	24.7	148	4.94	5.434	9.88
M7	10	444.6	700	1136	49.4	148	4.94	5.434	9.88
M8	15	420	700	1136	74.1	148	4.94	5.434	9.88

B. Experimental Methodology

The methodology used in this study to evaluate the effects of self-healing consists of four stages:

1. Determination of mechanical properties of Control Concrete (CC), Concrete with Silica fume, Concrete with Crystalline admixture (CCA), and Combination of both Crystalline admixture and Silica fume at 28 days.
2. Creation of control damage in the specimens
3. Simulation of the conditions/ Environmental exposures needed to achieve better healing results.
4. Evaluation of the regained mechanical properties and compare with results measured in stage 1.

A total 16 group of specimens were cast, each group consists 3 cubes, 3 cylinders and 3 beams were casted. Four groups are used for improvement of strength characteristics. They are: Control Concrete (CC), Concrete with Silica Fume (CC+SF), Concrete with Crystalline Admixture (CC+CA), and Concrete with Silica Fume and Crystalline Admixture (CC+SF+CA). 12 groups are used for Structural Cracks self-healing study under four exposure conditions respectively.

1) *Determination of Mechanical Properties:* Mechanical Properties studied in this study are 1.Compressive strength 2.Split tensile strength and 3.Flexural tensile strength.

2) *Creation of damage (Pre-cracking Process):* Cube Specimens(100X100X100mm) and Cylindrical specimens(100X200mm) were pre-cracked at the age of 28 days for structural cracks, by means of a compression and split tensile test, a controlled damage : this was meant as the width of the crack, which was set to reach a target value, controlled by a loading. The measure of the crack width with the calibration ruler in optical micrometer while performing the compression and splitting test has been meant as good enough to obtain crack widths within a range of 0.1–0.4 mm.

3) *Exposure Simulation :* Four Environmental exposure conditions were considered in order to determine the influence of water availability and its temperature on the self healing capability of the tested specimens, comparing reference concrete with silica fume and crystalline admixture concrete. All specimens were left to heal for 42 days.

Exposures	Conditions
Water Immersion	Continuous immersion in tap water at laboratory conditions only adding water to compensate for evaporation.
Wet/Dry Cycles	Water immersion in tap water for 3.5 days and air exposure for others 3.5 days.
Water Contact	A layer of water of 2cm on one surface, additional water was supplied to maintain the water level.
Air Exposure	Storage of the specimens in normal laboratory conditions inside a room without exterior influences on air conditions.

4) Evaluation of the Regained Mechanical Properties: Determine the regained mechanical properties after healing cracks in concrete specimens under four different environment exposures and compare with the properties measured in 2.2.1

III. RESULTS AND DISCUSSIONS

A. Compressive Strength

Compressive strength of M70 concrete with partial replacement of cement by Silica fume is increases up to 10% replacement and with further increase in Silica fume the compressive strength decreases. The maximum compressive strength of 84.91N/mm^2 is achieved for the concrete mix with 10% replacement of cement by silica fume which is 4.45% more than that of reference mix (S_0) for 28 days curing. At the age of 28 days, specimens were pre-cracked to introduce a structural crack width of 0.1-0.4mm. Thereafter, pre-cracked specimens are tested after Self- healing of cracks, the regain mechanical properties after healing of structural cracks under four different exposures as shown in table 2.

TABLE II
REGAINED COMPRESSIVE STRENGTH OF HSC (M70) UNDER FOUR EXPOSURES DUE TO SELF-HEALING OF STRUCTURAL CRACKS

Mixes	% of SF	% of CA	Compressive strength@28days in Mpa	Regained compressive strength@ 28 days				Regained compressive strength @ 42 days			
				WI	W/D	WC	AE	WI	W/D	WC	AE
S_0	0	0	81.29	34.10	33.52	32.45	30.33	35.60	34.32	33.87	31.11
S_5	5	0	82.37	40.59	39.81	39.03	38.56	42.13	41.35	39.98	39.05
S_{10}	10	0	84.91	51.60	50.97	50.14	46.01	54.31	53.88	52.67	48.29
S_{15}	15	0	83.07	45.16	44.73	44.07	43.29	47.77	45.63	44.91	44.56
CA	0	1.1	85.94	79.02	75.18	68.56	58.91	88.17	86.83	72.77	63.22
S_5CA	5	1.1	86.17	80.23	78.16	69.37	60.53	89.03	87.41	74.57	63.51
S_{10}CA	10	1.1	88.10	83.15	81.26	72.38	65.05	92.29	89.55	77.89	65.32
S_{15}CA	15	1.1	87.19	81.50	79.35	70.55	62.29	90.17	88.36	75.88	64.35

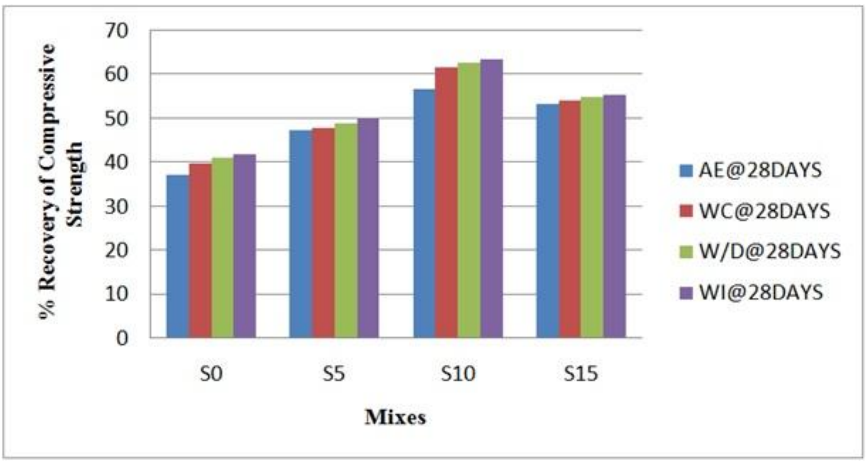

Fig.1 Variation of % Recovery of Compressive strength of HSC (M70) with silica fume under four exposures due to self-healing of Structural cracks after 28 days curing.

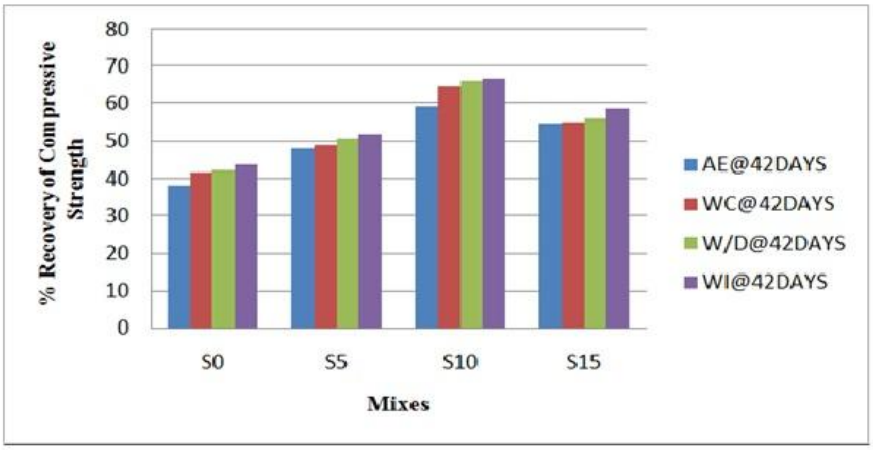

Fig .2 Variation of % Recovery of Compressive strength of HSC (M70) with silica fume under four exposures due to self-healing of Structural cracks after 42 days curing.

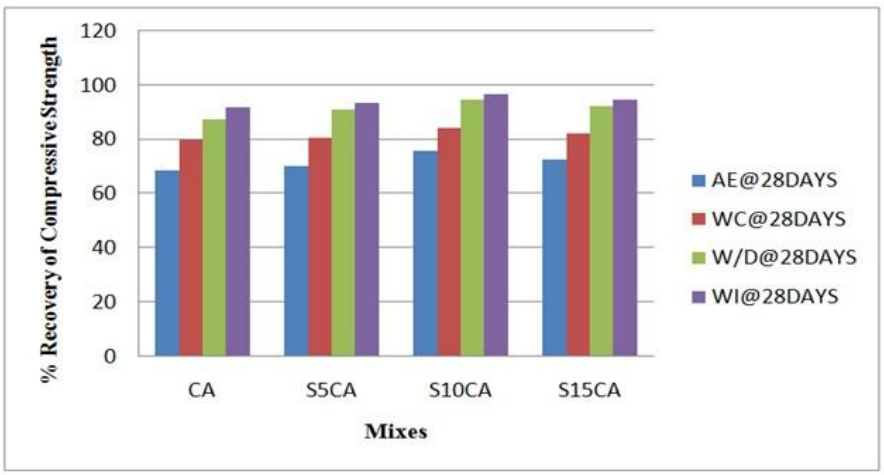

Fig.3 Variation of % Recovery of Compressive strength of HSC (M70) with silica fume and CCA under four exposures due to self-healing of Structural cracks after 28 days curing.

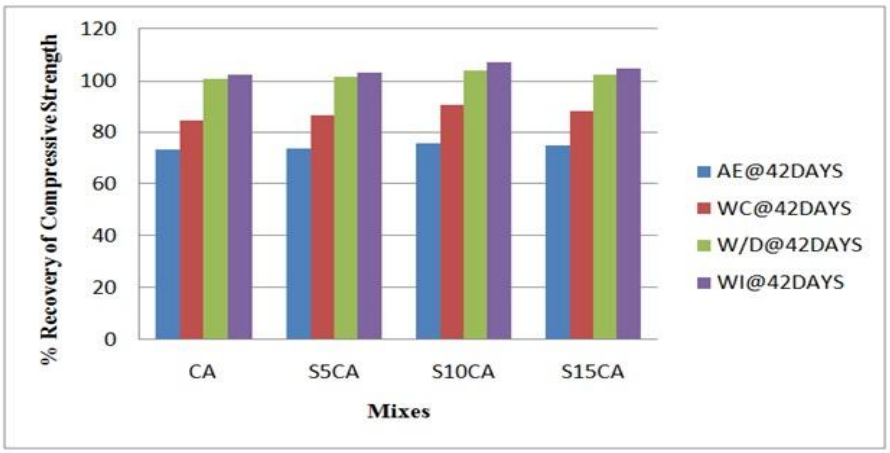

Fig. 4 Variation of % Recovery of Compressive strength of HSC (M70) with silica fume and CCA under four exposures due to self-healing of Structural cracks after 42 days curing.

B. Split Tensile Strength

Split tensile strength of HSC (M70) with partial replacement of Cement by Silica fume is increased up to 10% replacement of sand and with further increase in Silica fume the split tensile strength decreases. The maximum split tensile strength of 4.98 N/mm^2 is achieved for the concrete mix 10% replacement of cement by silica fume which is 18.57 % more than that of reference mix (S_0) for 28 days curing. At the age of 28 days, specimens were pre-cracked to introduce a structural crack width of 0.1-0.4mm. Thereafter, pre-cracked specimens are tested after Self- healing of cracks, the regain mechanical properties after healing of structural cracks under four different exposures as shown in Table 4.

TABLE III
REGAINED SPLIT TENSILE STRENGTH OF HSC (M70) UNDER FOUR EXPOSURES DUE TO SELF-HEALING OF STRUCTURAL CRACKS

Mixes	% of SF	% of CA	Split tensile strength@28days in Mpa	Regained Split tensile strength@ 28 days				Regained split tensile strength @ 42 days			
				WI	W/D	WC	AE	WI	W/D	WC	AE
S_0	0	0	4.20	1.83	1.74	1.63	1.20	2.03	1.85	1.75	1.22
S_5	5	0	4.65	2.23	2.11	1.75	1.48	2.51	2.38	2.09	1.75
S_{10}	10	0	4.98	2.95	2.74	2.31	1.82	3.20	3.03	2.43	2.12
S_{15}	15	0	4.73	2.83	2.59	2.16	1.68	2.95	2.71	2.25	1.97
CA	0	1.1	5.18	4.62	4.59	3.20	2.10	5.20	5.11	3.33	2.25
S_5CA	5	1.1	5.25	4.87	4.71	3.37	2.17	5.28	5.17	3.45	2.44
S_{10}CA	10	1.1	5.31	5.02	4.94	3.56	2.30	5.39	5.26	3.73	2.62
S_{15}CA	15	1.1	5.26	4.93	4.81	3.41	2.21	5.30	5.20	3.55	2.55

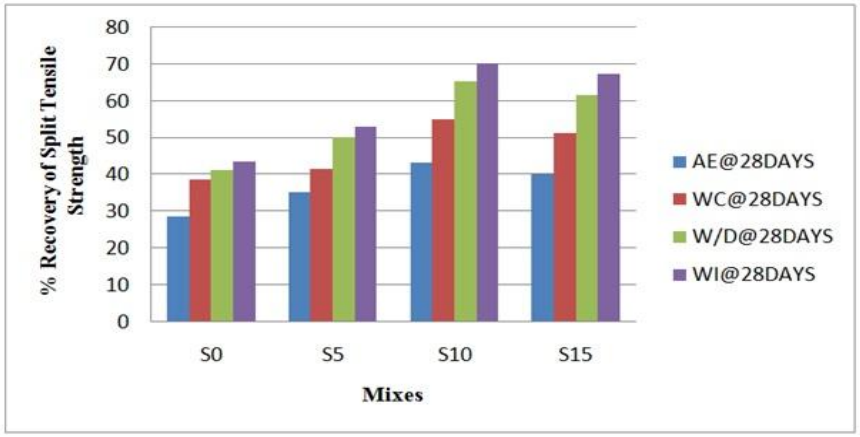

Fig.5 Variation of % Recovery of Split tensile strength of HSC (M70) with silica fume under four exposures due to self-healing of Structural cracks after 28 days curing.

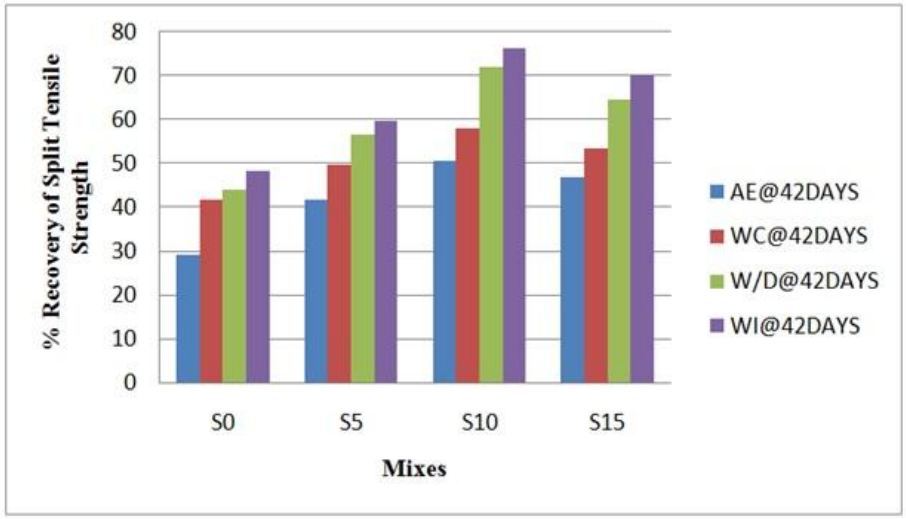

Fig.6 Variation of % Recovery of Split tensile strength of HSC (M70) with silica fume under four exposures due to self-healing of Structural cracks after 42 days curing.

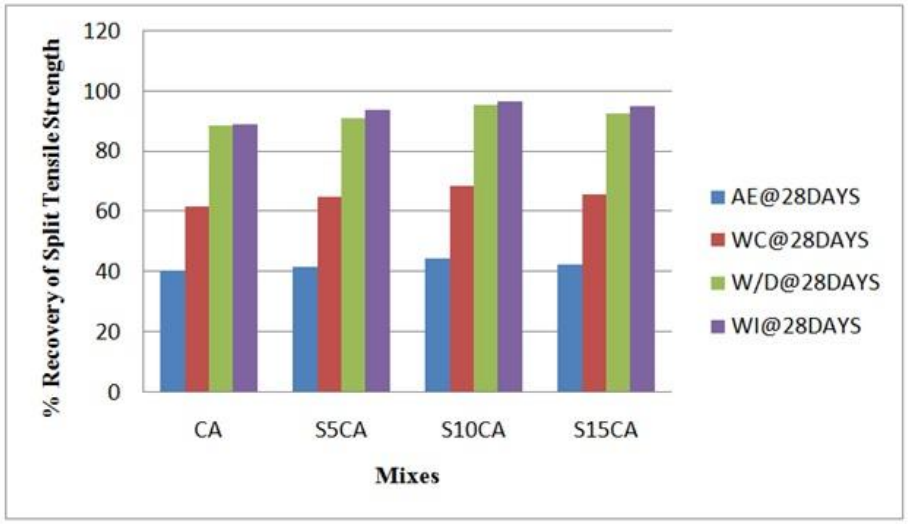

Fig.7 Variation of % Recovery of Split tensile strength of HSC (M70) with silica fume and CCA under four exposures due to self-healing of Structural cracks after 28 days curing.

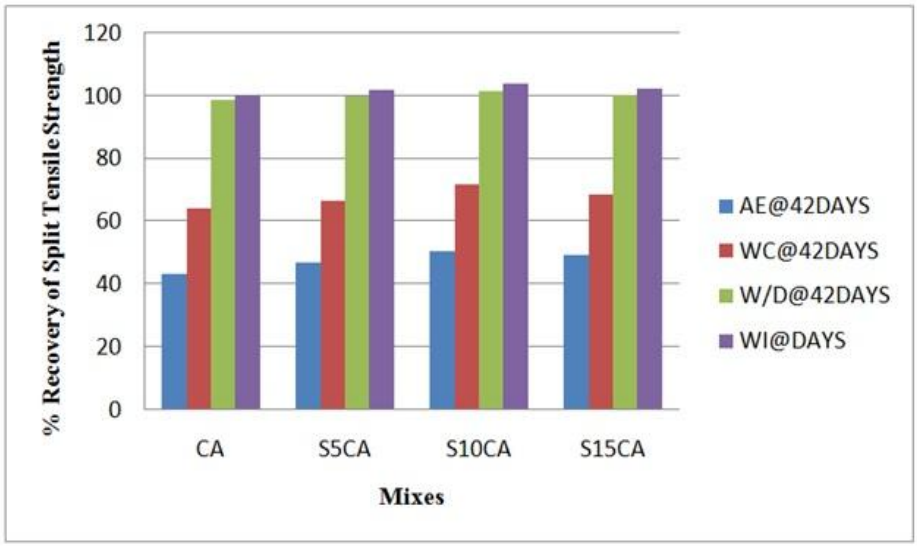

Fig.8 Variation of % Recovery of Split tensile strength of HSC (M70) with silica fume and CCA under four exposures due to self-healing of Structural cracks after 42 days curing.

IV. CONCLUSIONS

This study investigates the Self-healing behaviour of High strength concrete with Silica fume and crystalline admixture. After 28 days of curing, the specimens were pre-cracked with subsequent healing in different exposure conditions. The recovery of mechanical properties was investigated.

1. The mechanical properties of pre-cracked specimens with 10% of silica fume and 1.1% of Crystalline admixture has complete crack closing ability and 100% strength regained for WI, W/D and partially regained for WC and AE.
2. The maximum compressive strength of 88.10 N/mm² is achieved for mix S_{10}CA, which is 3.12% more than that of control mix (CA) for 28 days of curing.
3. The regained compressive strength of 92.29 N/mm² for 42 days of curing at water-immersion.
4. The maximum Split tensile strength of 5.31 N/mm² is achieved for mix S_{10}CA, which is 3.12% more than that of control mix (CA) for 28 days of curing.
5. The regained Split tensile strength of 5.75 N/mm² for 42 days of curing at water-immersion.

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