Versatility At Its Best: An Integrated Review On Development Of Self-Compacting Concrete

Mervin Ealiyas Mathews, Nandhagopal M, N.Anand, G. Prince Arulraj

Abstract: The sustainability of the construction industry is being vital instead of choosing random choices because the bond between the economy and the environment must be correlated. Here comes the role of Self-Compacting Concrete (SCC) ahead of Normally Vibrated concrete (NVC) due to the increased powder content and paste volume, it is possible to develop SCC with the use of unprocessed waste products as Supplementary Cementitious Materials(SCM). Thereby it is possible to achieve high-quality SCC with adequate strength and durability for the construction execution. From the review of literature, an extensive comparative study has been made for the various SCM used for the development of SCC. Rheological, durability and mechanical properties were examined. Findings revealed the possible extent of using waste materials rather than mere choices are valuable in case of the development of SCC that will give a potential move towards the green ecology and environment, thereby provides an idea for moving the construction industry towards sustainability.

Index Terms: Self-compacting concrete, Perlite aggregate, Sustainability, Workability, Durability.

1. INTRODUCTION

SCC is introduced as an innovatory form of NVC, which does not require vibration and consolidation during placement. SCC with its own weight, fills the formwork and flow through the spaces between reinforcements where NVC generates congestions. This gives importance to an extensive research in the field of development of SCC. The flexible qualities of SCC are flow ability, passing ability and filling ability. This inherent rheological properties helps to reduce the time and cost required for the construction. Recently, in contrast with the sustainable methodologies adopted in construction industry SCC developed as a blend concrete with the addition of SCM or Filler Materials (FM) from the waste materials are found to gain more importance. The proportioning of the SCC mix must be altered compared to NVC in order to achieve the flexibility qualities (Fig.1). The process must be initiated with analyzing the rheological properties and later with the mechanical and durability properties. The flow and segregation resistance of SCC can be enhanced by adding Super Plasticizer (SP) and a stabilizer known as Viscosity Modifying Agent (VMA). VMA is used if required to resist segregation and bleeding for the concrete with high w/c ratio. Increased fine content with low clinker content supported with supplementary materials such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF), Metakaolin (MK), Lime Stone Filler (LSF) etc. is experiencing much in the development of SCC.

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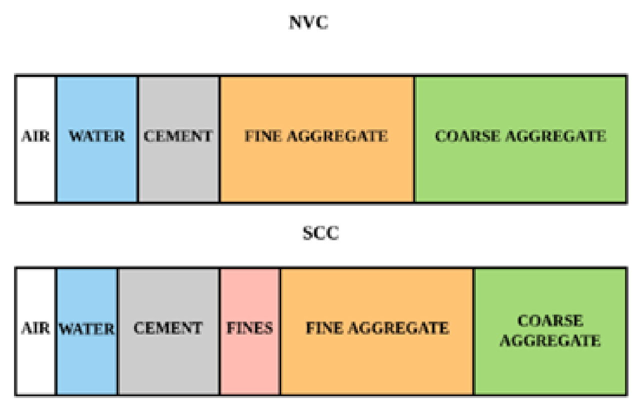

Fig. 1. *Typical mix proportion of NVC and SCC*

2 REVIEW OF LITERATURES

An extensive review of literature is carried out on the fresh, hardened and durability properties of SCC. The significant outcome obtained from the analysis indicates that the potential contribution of admixtures on the strength and durability properties of SCC.

2.1 Development and Durability Aspects of SCC

Mouhcine Benaicha et al. (2019) used LSF and SF as the mineral additives to develop the SCC. Various rheological properties such as slump flow, V-funnel, yield stress, viscosity and mechanical properties such as compressive strength and young's modulus were assessed for the various dosages of mineral admixtures. The experimental data revealed that the addition of LSF increased the workability but the increased dosage of SF reduced the flow properties. Also a relation proposed to estimate the compressive strength and young's modulus from the rheological behavior of SCC mixes developed with LSF and SF [1].Danuta Barnat-Hunek et al. (2018) investigated the effect on durability and mechanical properties of self-compacting lightweight concrete (SCLC) developed with lightweight perlite aggregate and light weight fibers such as Basalt Fiber (BF) and Steel Fiber (SF). For the development of SCC, BF dosage varied in a range from 0.5 to 1 % and SF as 0.5% in the mix. The porous perlite aggregate was used in the mixture between 5% and 15% as replacement. The workability, mechanical, durability and microstructural characteristics were analyzed. Results revealed that the hybrid fiber reinforced SCC mixture showed improved ductility behavior compared to that of other mixes. SF behaved as a crack arrester and BF showed an improvement in the case of frost attack [2].Tahir Gonen and Salih Yazicioglu (2018) studied the influence of type of curing in durability characteristics of the SCLC compared to the Conventionally Vibrated Light Weight Concrete (CVLC). A constant dosage of powder (550kg/m^3), in which 440kg/m^3 was cement and 110kg/m^3 of FA was used for the proportioning of mixture. Basaltic Pumice Aggregate (BPA) was replaced with Expanded Perlite Aggregate (EPA) by a level of 10, 20 and 30%. The SCLC mixtures were undergone air cooling and water cooling, which is then analyzed for water absorption, permeability and accelerated corrosion tests compared with CVLC mix. Results showed that the use of porous aggregate reduced the permeation and absorption capacity of the SCLC which will inversely affect the durability. Also the developed SCLC mix was more efficient than the other mixtures [3].Karthika et al. (2018) focused on the structural integrity of Light Weight Self- Compacting Concrete (LWSCC) developed with GGBFS and Rice Husk Ash (RHA) along with pumice stone as a replacement for coarse aggregate. Flow parameters and structural properties are tested and research outcome revealed that the replacement of pumice stone in a range of 30-40% enhanced the mechanical properties. It is found that the pumice stone is weaker in compression can be used as an additive along with suitable mineral admixtures [4].Wan et al. (2018) developed LWSCC using materials such as

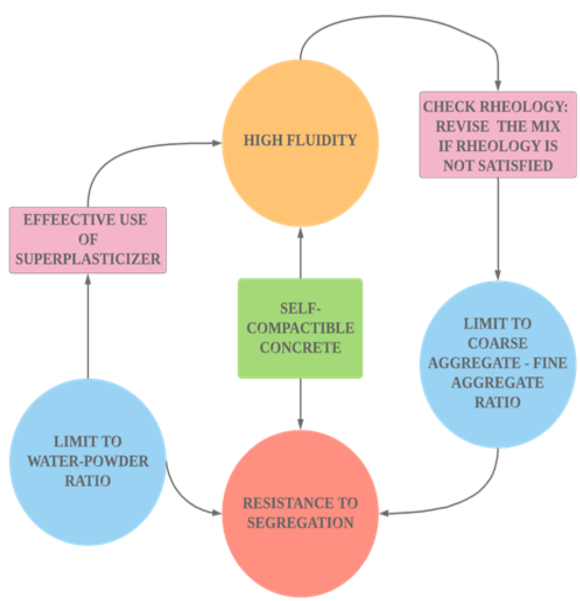

Fig. 2. *Work flow to achieve SCC*

Perlite, scoria and polystyrene by replacing fine aggregate. The fresh and hardened properties of the developed mixes are tested at 7 and 28 days. Results revealed that almost all the mixes considered for testing satisfied the requirement of self-compacting nature proposed by European Federation of National Associations Representing for Concrete (EFNARC) guidelines. The major outcomes of the study was that as the light weight content is increased in the mix, the workability and compressive strength is decreased, but the fluidity and segregation increased as the binder content is increased. Addition of perlite and scoria showed the significant reduction in strength. Mix with polystyrene showed the reduction in compressive strength of 33.3, 47.5, and 51.3% for 10, 20, and 30% replacements respectively.SCC usually contain higher paste volume than the NVC so as to reduce the frictional resistance between the solid phases in the mixture and also to achieve the fluidity (Fig2). It was understood that the role of cement paste is vital in the development of SCC as a filler and binder.

2.2 Behavioral Studies on SCC under Elevated Temperature

Mehmet Karatas et al. (2019) evaluated the mechanical and durability properties of Steel Fiber Reinforced Self-Compacting Concrete (SFRCC) developed with different percentage of Pumice Powder (PP). The developed mix was exposed to higher temperature. Powder content and water/powder ratio was kept constant in all the mixes. The PP was replaced with cement by weight basis of 5, 10, 15 and 20% and compared with control mix. Mechanical properties such as compressive strength, flexural tensile strength and durability characteristics such as porosity was examined for the mixtures and the mechanical properties are related with the durability properties. The cube compressive strength was determined by compression test as well as Ultrasonic Pulse Velocity (UPV) test. A detailed comparison was made on different mixes which are exposed to different temperatures such as 200, 400, 600 and 800°C (Fig.3). Tests results showed an improvement in strength for all the mixtures up to 200°C and a significant reduction in strength of about 60% at 800°C [6].

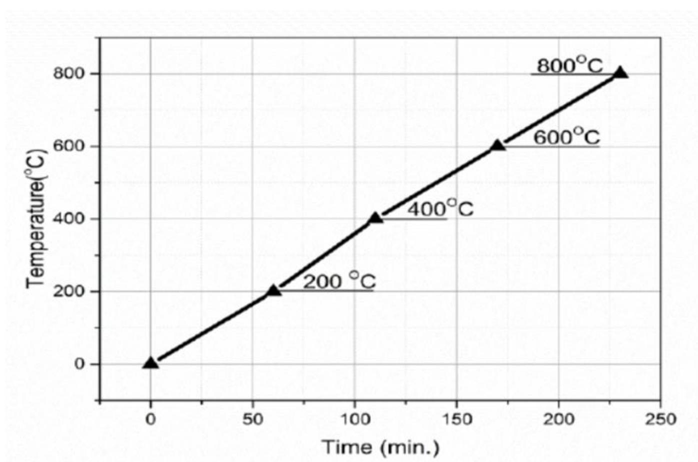

Fig. 3. *Time-Temperature Curve (Karatas 2019)*

Subhan Ahmad et al. (2019) investigated out the experiments on fresh and mechanical properties of SCC containing SF as the replacement for cement. The SF content was varied in the mixture in a range of 0, 2, 4, 6, 8, and 10 %. The workability properties such as flow ability, filling ability, passing ability, segregation resistance and hardened properties such as compressive, tensile and flexural strength are evaluated for heating regime of 200, 400, 600 and 800°C. Results indicated that the increased level of SF content reduced the workability properties but the hardened properties increased with the increase of SF content and it was found to be in the mix with 10% of SF replacement. Residual mechanical properties also shown the similar characteristics with the increase of SF content [7].Natarajan et al. (2019) investigated the effect of mechanical properties such as compressive strength and flexural strength of SCC which contains Nano Silica (NS) and Glass Powder (GP). The GP serves as a substitute material for fine aggregate varying such as 10, 20, 30, 40 and 50%. The variation in the structural properties was analyzed both in normal and elevated temperature. The temperature varied in the range of 200°C to 800°C with an increment. The effect of gradual (air cooling) and sudden cooling (water cooling) on the structural strength of specimen was also assessed during the investigation (Fig.4). The results revealed that the glass powder content added in the concrete has improved the thermal properties and the inclusion of NS enhanced the strength properties. It was recommended that the gradual cooling suggested in order to retain the strength properties stable than a sudden cooling [8].

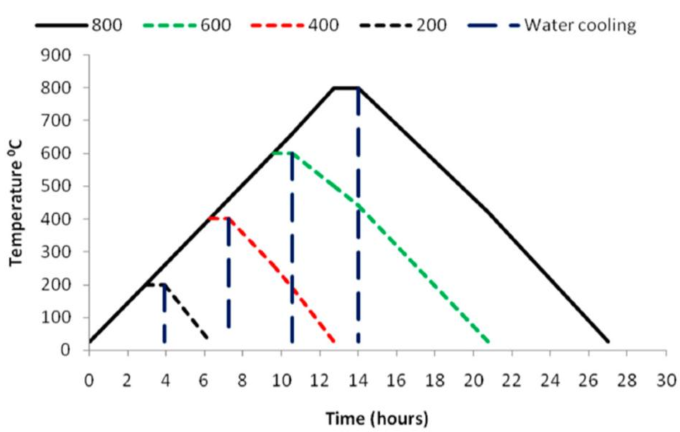

Fig. 4. *Temperature regime for water and air cooling (Natarajan 2019)*

Anand. N et al. (2016) made an attempt to study the effect of SF, FA, and MK on the strength properties of SCC subjected to elevated temperature. Poly Carboxylic Ether Based (PCEB) SP was used in the SCC mix. Mechanical properties such as compressive, tensile and flexural strength was compared for two different cooling regimes such as by air and water. Significant strength reduction was observed in the results for all the SCC mix, also noticed that strength reduction was higher for water cooled specimens than air cooled specimens. Mix developed with SF exhibited better residual strength compared to other SCC mixes with FA and MK. Microstructural analysis also carried out to analyze the specimens exposed to high temperature [9].Anand. N et al. (2014) conducted experimental studies to interpret the behavior of SCC specimens subjected to higher temperature. Specimens exposed to high temperature are either cooled by air or water. SCC mixes with strength grades varies as M25, M30, M35, M40 were developed and tested its mechanical strength properties. The results revealed that the strength loss is on the higher side for concrete with higher grade than concrete with lower grade of SCC mixes. Also it was found that the loss in mechanical properties depends on the cooling regime of fire exposed specimen [10].

2.3 Experimental Investigations on the Bond Behavior of SCC

Piotr Dybel and Daniel Walach (2018) conducted an investigation on the bond strength of concrete with steel in HPSCC. Pull out test was used to study the bond strength behavior. SF is used as the SCM replacing cement by 5, 10 and 15%. For determining the bond behavior of different levels of specimen the height of the sample was varied from 160 mm to 1600 mm. The placement of rebar was perpendicular to the direction of casting. Analysis revealed that the SF as SCM improved the bond strength characteristics. Also showed that the rebar orientation with respect to the casting face has no importance [11].Wesam K. A. Al-Fouadi et al. (2018) made an effort to investigate the bond behavior of concrete specimen with varying depth. Pull-out test was conducted for 32 samples experimentally and verified the analysis pattern using a FE software. Experimental work was categorized into Normal weight Self-Compacting Concrete (NWSCC) and Light Weight Self-Compacting Concrete (LWSCC). Each sample was divided into 4 levels and steel bars were embedded in each level i.e. one at top and bottom, two at the middle portion. Pull-out force and corresponding slip was measured from the bond test. The study showed that the bond strength was greater in NWSCC than LWSCC for all the cases. The comparison of experimental and analytical study showed identical results with small variation [12].Ahmet Benli et al. (2017) conducted an experimental investigation on the bond strength of Self-Compacting Motars (SCM) in which Ground Pumice Powder (GPP) was used as mineral additive. Six mixes including control mix and five different mixes of GPP with 7, 12, 17, 22 and 27% of cement as replacement used in the experiment. Fresh properties as well as hardened properties such as compressive strength and flexural strength along with the bond parameters are investigated in the research. It is observed that SCM with 12% replacement of GPP by weight of cement exhibited highest bond strength as compared to other mixes. An increase in compressive strength of 12% was observed replacement [13]. The bond strength was determined by pull out test and the generalized equations developed to calculate the bond strength (karakoc, 1985) is

$$\tau = P / (\pi . d . l) \quad (1)$$

TABLE 1
DATABASE FOR MIX PROPORTIONING OF SCC

Reference	Details of Chemical Admixture				Test Age	No. of Mixes	Details of Aggregate		Cement	Mineral Admixture (SCM/FM)
	Type of SP	Volume (Kg/m3)	VMA Type	Volume (Kg/m3)			Fine	Coarse		
Benaicha et al. (Morocco, 2019)	MPCP	0.5% of Binder Content	N.A.	N.A.	1, 7, 28	13	Sand < 2mm	< 10mm	CEM I (grade 52.5)	LSF, SF
Hunek et al. (Poland, 2018)	PCEB	2% of Binder Content	N.A.	N.A.	7, 28	6	Quartz sand, Perlite < 2mm	Granite aggregate 2-8mm	CEM I (grade 42.5)	SF
Tahir Gonen and Salih Yazicioglu (Turkey, 2018)	PCEB	N.A.	N.A.	N.A.	28	7	Basaltic pumice, River, Expanded perlite < 4mm	Basaltic pumice, River < 16mm	CEM I (grade 42.5)	FA
Karthika et al. (India, 2018)	PCEB	4.64	N.A.	N.A.	7, 14, 28	9	River Sand < 4.75mm	Pumice Stone < 10mm	OPC (grade 43)	GGBS,RHA
Wan et al.	Type SN	4.2	Type SN	0.85	7, 28	15	Perlite, scoria, and polystyrene <4.75 mm	<10mm	GPC	FA, GGBS, SF
Karatas et al. (Turkey, 2019)	N.A.	6	N.A.	N.A.	3, 7, 28, 90	5	River sand < 4mm	< 16mm	CEM I (grade 42.5)	GPP
Ahmad et al. (India, 2019)	PCEB	1.2% of Binder Content	N.A.	0.3% of Cement Content	7, 28	6	Sand < 4.75mm	< 12.5mm	OPC (grade 53)	SF
Natarajan et al. (India, 2019)	NB	1.2% of Cement Content	N.A.	N.A.	7, 14, 28	6	River Sand, GP< 4.75mm	N.A.	OPC (grade 43)	NS
Anand et al. (India, 2016)	PCEB	1-2% of Binder Content	N.A.	<1% of Binder Content	28	15	River Sand < 4.75mm	< 12.5mm	OPC	FA, SF, MK
N Anand and G. Prince Arulraj (India, 2014)	PCEB	0.8-1.2% of Binder Content	Glenium Stream 2	<0.1% of Binder Content	28, 56	4	River Sand < 4.75mm	Granite stones <10mm	OPC	FA
Piotr Dybel and Daniel Walach (Poland, 2018)	N.A.	5.85	N.A.	N.A.	28	4	Sand < 2mm	Basalt aggregate < 8mm	CEM I (grade 42.5)	SF
Wesam K. A. Al-Fouadi et al. (Turkey, 2018)	N.A.	4.80	N.A.	N.A.	56	8	NWA,LWA< 4mm	NWA,LWA< 16mm	N.A.	FA
Ahmet Benli et al. (Turkey, 2017)	PCEB	7	N.A.	N.A.	3, 28, 90	6	River Sand < 4mm	N.A.	CEM I (grade 42.5)	GPP
Nipun Verma and Anil Kumar (India, 2015)Misra	PCEB	7.3	N.A.	N.A.	3, 7, 28	6	River Sand < 4.75mm	OPC (grade 53)	OPC (grade 33)	SF
Golafshani et al.	PCEB	0.7% & 1% of Cement Content	N.A.	N.A.	28	2	River Sand < 4.75mm	Lime stones <12mm	CEM I	SF

OPC- Ordinary Portland Cement, NWA- Normal Weight Aggregate, LWA- Light Weight Aggregate, PCEB- Poly Carboxylic Ether based, N.A- Not Available, GPC- General Purpose Cement

TABLE 2
DATABASE FOR EXPERIMENTAL RESULTS (BOND STRENGTH)

Reference	Size of the Specimen	Rate of heating	Compressive Strength(MPa)	Duration of Heating	Temperatures	Residual Compressive Strength (%)
Benaicha et al.	Cylinder 160 x 320 mm	N.A.	77.1	N.A.	N.A.	N.A.
Hunek et al.	Cube 150 x 150 x 150 mm	N.A.	74.63	N.A.	N.A.	N.A.
Tahir Gonen and Salih Yazicioglu	Cube 100 x 100 x 100 mm	N.A.	65.6	N.A.	N.A.	N.A.
Karthika et al.	Cube 150 x 150 x 150 mm	N.A.	47.5	N.A.	N.A.	N.A.
Wan et al.	Cylinder 100 x 200 mm	N.A.	N.A.	54.20	N.A.	N.A.
Karatas et al.	Cube 150 x 150 x 150 mm	N.A.	84.75	60, 120, 180, 240 mins	200, 400, 600, 800°C	101.75, 98.21, 75.47, 39.30
Ahmad et al.	Cylinder 150 x 300 mm	3°C/min	52.32	Peak temperature maintained for 120 mins	200, 400, 600°C	84.40, 50, 32.74
Natarajan et al.	Cube 50 x 50 x 50 mm	20°C/min	68	Till the desired temperature is attained	200, 400, 600, 800°C	95.58(A/C), 80.88(W/C)
Anand et al.	Cube 150 x 150 x 150 mm	N.A.	22.13, 24.68, 26.95 (SF, FA, MK)- M20 (W/C)	Till the desired temperature is attained	27°C-900°C	46, 59.20, 68.70
N Anand and G. Prince Arulraj	Cube 150 x 150 x 150 mm	N.A.	31.25, 36.39, 42.80, 47.55 – (M25-M40)	27°C-900°C, Peak temperature maintained for 90 mins	27°C-900°C, 900°C @ 90mins	51.42(A/C-900°C @ 90mins) , 52.8, 54.1, 56.3
Piotr Dybeł and Daniel Wałach	Cube 150 x 150 x 150 mm	N.A.	90.2	N.A.	N.A.	N.A.
Wesam K. A. Al-Fouadi et al.	Cube 150 x 150 x 150 mm	N.A.	85.40	N.A.	N.A.	N.A.
Ahmet Benli et al.	Cube 40 x 40 x 150 mm	N.A.	81.15	N.A.	N.A.	N.A.
Golafshani et al.	Cube 200 x 200 x 200 mm	N.A.	44.88, 59.77 (M45 & M60)	N.A.	N.A.	N.A.

TABLE 3
DATABASE FOR EXPERIMENTAL RESULTS (COMPRESSIVE STRENGTH)

Reference	Size of the Specimen	Bar Diameter (mm)	Rate of heating	Compressive Strength(MPa)	Pull-out force (kN)/Bond Strength/Normalized Bond Strength (MPa)	Duration of Heating	Temperatures	Residual Bond Strength (%)
Piotr Dybeł and Daniel Wałach	Cube 160 x 160 x 160 mm	10	N.A.	90.2	3.75	N.A.	N.A.	N.A.
Wesam K. A. Al-Fouadi et al.	Cube 150 x 150 x 150 mm	16	N.A.	85.40	129.63 kN	N.A.	N.A.	N.A.
Ahmet Benli et al.	Cube 150 x 150 x 150 mm	20	N.A.	81.15	11.71	N.A.	N.A.	N.A.
Nipun Verma and Anil Kumar Misra	Cube 150 x 150 x 150 mm	16	N.A.	N.A.	10.52	N.A.	N.A.	N.A.
Golafshani et al.	Cube 200 x 200 x 200 mm	16	N.A.	44.88, 59.77 (M45 & M60)	30.62 kN, 34.70kN (Bars placed vertically)	N.A.	N.A.	N.A.

A/C- Air Cooling, W/C- Water Cooling

TABLE 4
DATABASE FOR EXPERIMENTAL RESULTS (FLEXURAL STRENGTH)

Reference	Size of the Specimen	Rate of heating	Compressive Strength(MPa)	Flexural Strength(MPa)	Duration of Heating	Temperatures	Residual Flexural Strength (%)
Hunek et al.	100 x 100 x 500 mm	N.A.	74.63	9.56	N.A.	N.A.	N.A.
Karthika et al.	100 x 100 x 500 mm	N.A.	47.50	8.20	N.A.	N.A.	N.A.
Karatas et al.	100 x 100 x 350 mm	N.A.	84.75	5.03	N.A.	N.A.	N.A.
Ahmad et al.	100 x 100 x 500 mm	3°C/min	52.32	6.74	Peak temperature maintained for 120 mins	200, 400, 600°C	75.96,43.03, 27
Natarajan et al.	160 x 40 x 40 mm	20°C/min	68	8.20	Till the desired temperature is attained	200, 400, 600, 800°C	79.27(A/C), 71.95(W/C)
Anand et al.	100 x 100 x 500 mm	N.A.	22.13, 24.68, 26.95 (SF, FA, MK)- M20 (W/C)	5.19, 5.39, 5.54	Till the desired temperature is attained	27°C-900°C	48.55, 50.83, 60.10
N Anand and G. Prince Arulraj	100 x 100 x 500 mm	N.A.	31.25, 36.39, 42.80, 47.55 – (M25-M40)	2.72, 3.56, 4.02, 4.45	27°C-900°C, Peak temperature maintained for 90 mins	27°C-900°C, 900°C @ 90 mins	58.24(A/C-900°C @ 90mins) , 59.7, 61.8, 62.9
Ahmet Benli et al.	Cube 40 x 40 x 150 mm	N.A.	81.15	11.45	N.A.	N.A.	N.A.

TABLE 5
DATABASE FOR EXPERIMENTAL RESULTS (TENSILE STRENGTH)

Reference	Size of the Specimen	Rate of heating	Compressive Strength(MPa)	Tensile Strength(MPa)	Duration of Heating	Temperatures	Residual Tensile Strength (%)
Karthika et al.	Cylinder 100 x 200 mm	N.A.	47.50	3.70	N.A.	N.A.	N.A.
Wan et al.	Cylinder 100 x 200 mm	N.A.	54.20	4.85	N.A.	N.A.	N.A.
Ahmad et al.	Cylinder 150 x 300 mm	3°C/min	52.32	5.09	Peak temperature maintained for 120 mins	200, 400 and 600°C	75.25, 48.92 and 27.90
Anand et al.	Cylinder 150 x 300 mm	N.A.	22.13, 24.68, 26.95 (SF, FA, MK)- M20 (W/C)	3.5, 3.80, 4.02	Till the desired temperature is attained	27°C-900°C	47.85, 50.26, 61.44
N Anand and G. Prince Arulraj	Cube 150 x 150 x 150 mm	N.A.	31.25, 36.39, 42.80, 47.55 – (M25-M40)	5.39, 5.91, 6.42, 6.95	27°C-900°C, Peak temperature maintained for 900 mins	27°C-900°C, 900°C @ 90mins	64.26(A/C-900°C @ 90mins) , 66.67, 67.96, 68.80
Wesam K. A. Al-Fouadi et al.	Cube 150 x 150 x 150 mm	N.A.	85.40	3.96	N.A.	N.A.	N.A.

Nipun Verma et al. (2015) carried out a comparative study on the bond strength of SCC and Normal Cement Concrete (NCC). The outcome of the study presented that SCC exhibited higher bond strength compared to NCC. The dosage of superplasticizer in SCC provides fluidity to the mix. For both the mixes of NCC and SCC, w/c ratio of 0.40 showed the maximum strength in 3, 7 and 28 days. It was reported that a rapid increase in bond strength observed for w/c ratio of 0.40 in SCC compared to NCC, but for w/c ratio of 0.50 and 0.60 the rate of gain in bond strength was almost equal for both the cases [14].Golafshani et al. (2014) studied the behavior of bond strength and failure modes of steel and Glass Fiber Reinforced Polymer (GFRP) bars embedded vertically in SCC. Results from the study revealed that the bond strength was higher in SCC with steel bars than the SCC with GFRP bars due to its sufficient adhesion treatment. At the top level of the specimen both steel and GFRP bars showed significant loss, i.e. averages loss of 5.5% for steel bars and 8% for GFRP bars in SCC. The vertically embedded bar specimen showed better strength behavior than horizontally embedded bar under pull out test. Also the strength variation was less in steel bars as compared to GFRP bars [15].A detailed database on mix design of SCC compressive strength, tensile strength, flexural strength and bond strength of SCC is shown from Table 1 to Table 4.

3 CONCLUSION

Based on the detailed literature review the effect of different mineral admixtures in the development and durability aspects of SCC has shown wide scope of research possibilities in the thrust area of advanced construction field. Different SCM and FM are being used for the analysis of strength parameters such as compression, tension, flexure and bond. Durability and mechanical properties of SCC subjected to elevated temperature is also reviewed in this paper. As an outcome, number of significant conclusions were obtained regarding the behavior of SCC in relation with NVC. Database on mix proportion, compressive, Tensile, flexural and bond strength of SCC shows that,

- Addition of mineral admixture in the concrete reduced the use of cement content significantly in concrete.
- SF shown better strength properties among the other SCM's.
- The ratio of cylinder to cube strength varies from 0.8 to 1.5 for compressive strength 20MPa to 80MPa.
- The bond strength of steel to concrete is either in relation with the compressive strength or the depth of the reinforcing bar embeded in concrete.
- The in situ condition for both the SCC and NVC are similar, but the mix design and mixing procedure plays a vital role in the performance for SCC.

Therefore, the comparative analysis based on the earlier studies in the past years will be helpful to formulate the new design procedure for the development of SCC.

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