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RESEARCH ARTICLE

Influence of blends of alkali resistant fibres and polypropylene fibres on fresh and hardened properties of early strength self compacting concrete

Pavan Kumar Diddi[1] · Pushpendra K. Sharma[1] · Amit Srivastava[1] · Sri Rama Chand Madduru[2] · E. Sreenivas Reddy[3]

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Abstract
Research outcome on merger of discrete short length fibres like steel fibre, polypropylene fibre (PPF), alkali resistant fibre (ARF) etc. to produce fibre reinforced concrete (FRC) gave a momentous thrust to FRC to use it for shrinkage resistance, crack bridging as well as improving the tensile load carrying resilience. Continuous research is going on FRC by incorporation of various size/shape combinations of similar fibre material or combinations of different fibre material to further improve the performance of FRC. The challenge of using combinations of various industrial by products having reactive and slow pozzolanic nature as part replacement of cement to reduce greenhouse gas emissions is also experimented world over for achieving sustainability in concrete construction activities. These pozzolanic materials [supplementary cementitious materials (SCM)] are also useful in proportioning self compacting concrete (SCC) which offer higher quantities of powder size material (0.125 mm size) as required for achieving qualifying characteristics of SCC. Innovations for improving the SCC to use it in fast track construction and repair projects is being made by several researches, by the way of incorporating various reactive material to attain fast setting, early strength and combine different fibres in to the SCC to have resistance to shrinkage, cracks and develop enough tensile strength in early age for opening the structure to users. Hence there exists a vast scope for research in FRC for improvement of performance by the way of incorporation of compatible materials and fibre combinations. In this study two types of hybrid fibre reinforced self compacting concrete were proportioned with part replacement of cement with metakaolin as reactive SCM and ground granulated blast furnace slag as normal reactive SCM. Various combinations of PPF and ARF investigated in SCC mix with a target to achieve 1 day compressive strength of 25 N/mm^2 and split tensile strength of 2 N/mm^2 for use in fast track construction and repair works. Mechanical strength tests and durability tests at early ages as well as up to 56 days conducted.

Keywords Reactive SCMs · GGBFS · Metakaolin · Alkali resistant fibres · Polypropylene fibers

✉ Pavan Kumar Diddi
dpavankumar.1976@gmail.com

Pushpendra K. Sharma
pushpendra.23437@lpu.co.in

Amit Srivastava
amit.22986@lpu.co.in

Sri Rama Chand Madduru
maddurusriram@gmail.com

E. Sreenivas Reddy
hyderabadtestlabs@gmail.com

1 Department of Civil Engineering, Lovely Professional University, Phagwara, India

2 Department of Civil Engineering, Sree Chaitanya College of Engineering, Karimnagar, India

3 M/S Hyderabad Test Labs and Engineering Services, Hyderabad, India

1 Introduction

Concrete, the second most consumed material after water, is widely used all over the world as the most favourable construction material for general construction works as well as engineered construction works [1]. It is well known that plain cement concrete (PCC) is strong in carrying compression loads but weak in counteracting tensile loads and hence to overcome this deficiency in concrete, reinforcement is added in a designed way enabling the resulting reinforced cement concrete to be able to withstand the tensile loads conveniently [2]. Addition of reinforcement in concrete in other forms was also being tried in several ways like with asbestos fibres, natural fibres, extracted fibre from animals etc. [3–6]. Research outcome on various experimentations that were carried on fibre reinforced concrete during early 1960's gave a significant thrust to fibre reinforced concrete (FRC) where discrete short length fibre, particularly steel fibre, was incorporated in plain concrete to improve its performance against cracking as well as improving its tensile load carrying stamina [6–10]. Several researchers tried and succeeded in improving the performance of concrete using various types of fibres like polypropylene fibre, PVA fibre, Glass fibre and so on [11–13]. It is generally accepted that incorporation of discrete fibres in concrete enhances the ductility and mechanical performance but due care to be taken to make the FRC workable, with the help of chemical admixtures, as the fibre additions in these concrete will reduce the workability of concrete compared to PCC at same water/cement ratio. Development of self-compacting concrete (SCC) during 1980's has also attracted various researchers to further experiment and thereby improve the SCC's performance by integration of various supplementary cementitious materials (SCMs) moderately reactive in nature like fly ash, slag powders and highly reactive ultrafine SCMs like metakaolin (MK), silica fume (SF), rice husk ash (RHA) etc., [14, 15]. Various types of fibres are being incorporated either single type or in various combination (popularly called as hybridization) for improving the performance of SCC. Experiments on flexural strength of concrete revealed that integration of long fibre in concrete slightly increased the flexural strength but no much increase observed in splitting tensile strength [16]. This is in contradiction to the findings where it was established that integration of fibres in concrete not only enhances the flexure strength but also the split tensile strength [17, 18]. Rupture strength of concrete observed to be increased as the % volume of fibre increases in concrete [19]. Steel fibres with hooked end in concrete exhibited superior performance compared to normal steel fibres [20]. Hoked end steel fibres will have advantage of anchoring effect because of its shape and hence will perform advantageously than the plain steel fibres in flexural strength of SCC and conventional concrete [21]. Fibre volume ratio proportionately effects the bending tensile strength of concrete [22–24]. The use of PPF, PVA etc. type of fibre improves the mechanical and durability properties of concrete. As steel is susceptible to corrosion in the same way steel fibres also have such kind of defect when admixed in concrete [25]. It was also established that short discrete fibres improves the shrinkage resistance as well as mechanical strength parameters [26] and long fibres are advantageous in bridging the cracks and improving the ductile behaviour of concrete [27–30]. Thus researchers are focussing their studies to experiment the effects of combinations of various sizes of fibres of similar materials [31–33] or various types of fibres of dissimilar materials [32] to improve the performance of concrete [34, 35]. The indication of expending these hybrid combinations of fibres in concrete is to improve the concrete performance both in macro scale as well as in micro scale [36]. As the earlier constructed concrete structures, constructed in the last fifty years or so, are becoming aged with the passage of time, there exists ample research opportunities to repair [37, 38], renovate, refurbish, restore these valuable assets in an engineered way in order to achieve sustainability by avoiding new constructions for some time and to improve the durability of concrete by suitable repairs as warranted [39–44] to achieve economy in operations and maintenance of these aged concrete infrastructures [45]. As the concrete infrastructure's repair, rehabilitation, refurbishment and renovation works are being massively taken world over, there is huge demand for the fast track construction and repair materials, construction techniques to enable the distressed infrastructure to put to reuse at the very earliest to meet the early opening times as well as to economise the repair and maintenance operations [46]. This urge necessitates to develop fast setting and early age strength gaining concrete mix proportions capable of conveniently flowing into each nooks and corners of formwork without any compaction and have enough compressive strength as well as flexural strength to tackle effectively the stresses and loads to which the structure is exposed when immediately opened to reuse after the repair works [47]. Proprietary repair materials and fast track construction solutions offered in the market by leading material manufacturers are often costly and are not readily available to meet the demand [48]. In some cases these materials fail due to incompatibility between the substrate and repair materials [49]. It was established that the existence of fibres in the hybrid combination in concrete or cement mortar significantly advances mechanical features like flexure strength, toughness etc. to an order of 6–12% when compared to conventional concrete [31–36]. It was also shown that adding different types of fibres (hybrid combinations) in the concrete, further enhancement of fresh state properties and hardened state properties resulted in fibre reinforced concretes [20–24]. The hybrid combinations of metal and synthetic fibres offered impending results in taming concrete characteristics and reducing the cost of fibre reinforced concrete [22]. Addition of hybrid combinations of low and high modulus flexible fibres of natural and synthetic verities in concrete resulted in early age cracking of concrete by arresting the micro and macro cracks respectively [50]. The literature review shows that the incorporation of hybrid combinations of steel fibres, synthetic fibres and natural fibre in various proportions will enhance the mechanical properties of concrete. In spite of these efforts in the vast literature, our consideration of what correctly institutes an optimal blend of fibres that is capable of producing supreme interaction in performance remains quite incomplete. Also there is less information available on the performance of various combinations of hybrid fibres like ARF, PPF, Steel, PVA, natural fibres etc. in early strength self compacting concrete, as there is growing need for fast track construction and repair works of concrete for early opening of the infrastructure facilities for intended use and early strength self compacting concrete, with sufficient flexural strength by incorporating discrete fibres of various materials in different combinations. In the near future fast track construction will become the trend for achieving the early opening of structures. Hence there is growing research need in development of compatible materials, combinations to develop fast track construction materials incorporating hybrid combinations of various fibres to enhance the tensile performance of concrete. Thus these gaps in research are motivating several researchers to work in the directions to develop early strength gaining concrete in a way as sustainable as possible. This has also motivated the authors to carry the present research with an objective of developing the hybrid fibre reinforced self compacting concrete with OPC and part replacement of OPC with moderately reactive SCMs (for sustainability point of view), ultrafine SCMs (for compensating the early age slow reactivity of moderately reactive SCMs), hybrid combinations of two types of synthetic fibre, in a suitable proportions yielding durable concretes, for enhancing the performance of concrete both in early ages, during maturity age and after maturity ages. The main aim of this experimental investigation was to proportion M50 grade SCC with an assumed standard deviation of 5 N/mm^2 and achieving a target mean strength of 58.25 N/mm^2 at 28 days. The total cementitious material (cm) used for the proportioning SCC mix was 550 kg/m^3 with a free water/cm ratio of 0.33, as per IS 10262:2019 [51] in order to meet SF1 flow criteria (550–650 mm) and Class2 criteria of V funnel flow time (9–25 s). Various combinations of polypropylene fibre (PPF) and alkali resistance fibre (ARF) in a total hybrid fibre content of 1% by volumetric proportion was experimented in this study on hybrid fibre reinforced early strength self compacting concrete. In the total cementitious material of 550 kg/m^3, 50% of ordinary portland cement (OPC) was replaced by a combination of 10% MK (as ultrafine SCM) [52], and 40% GGBFS (as moderately reactive SCM) [26]. The proportioned SCC mix was aimed to be of having characteristics of less prone to shrinkage, offer higher resistance against sulphate ion ingression and chloride ion ingression, to meet a target to achieve final setting within 10 h of placement of concrete and also to attain 1 day compressive strength of 25 N/mm^2 and split tensile strength of 2.0 N/mm^2.

2 Experiment design

In order to meet the targeted strength, this experimental study was designed to investigate various combinations of polypropylene fibre (PPF) and alkali resistance fibre (ARF) in a total hybrid fibre content of 1% by volumetric proportion [53–55] in the above proportioned SCC. Two types of hybrid fibre reinforced SCC (HyFSCC) mixes were investigated in this study. $HyFSCC_{Type1}$ was experimented with the fibre combinations of PPF and ARF as 1% PPF + 0%ARF; 0.7%PPF + 0.3%ARF; 0.6%PPF + 0.4%ARF and 0.5% PPF + 0.5%ARF. These mixes were designated as $HyFSCC_{Type1\text{-}A}$, $HyFSCC_{Type1\text{-}B}$, $HyFSCC_{Type1\text{-}C}$ and $HyFSCC_{Type1\text{-}D}$ respectively. Mix of $HyFSCC_{Type2}$ was experimented with the fibre combinations of PPF and ARF as 1% ARF + 0%PPF; 0.7%ARF + 0.3%PPF; 0.6%ARF + 0.4%PPF. These mixes were designated as $HyFSCC_{Type2\text{-}A}$, $HyFSCC_{Type2\text{-}B}$ and $HyFSCC_{Type1\text{-}C}$ respectively. To compare the properties of HyFSCC mix a control mix (SCC control) without adding any fibre was used. Fresh state properties of these HyFSCC mixes were studied with parameters of slump flow, V funnel flow time, setting time test as per relevant standards of IS 1199:2018 [54] and L Box flow obstruction ratio test as per EFNARC guidelines for SCC [55]. Hardened state SCC and HyFSCC mix characteristics were assessed at 1 day, 3 days, 7 days and 56 days ages for compressive strength, splitting tensile strength and shrinkage as per relevant Indian Standard IS 516:2018 [56]. Durability characteristics of SCC and HyFSCC mixes were assessed at 7 days, 28 days and 56 days, by testing the expansion of concrete specimens (prepared with the respective concrete mix screened through 4.75 mm sieve) on immersion in Na_2SO_4 (sulphate) solution, consisting of 50 g of Na_2SO_4 in 1 L solution prepared with distilled water, as the measure against sulphate ion ingression, as per ASTM C1012/C1012M [57] and the chloride content of concrete slab specimen's surface ponded with the 3%NaCl (chloride) solution (as the measure of chloride ion ingression) as per as per ASTM C-1543 [58]. The material characterisation, SCC and HyFSCC mix proportion, tests carried and the results of tests and analysis of the same is presented in the subsequent paras.

3 Materials

3.1 Cement

OPC 53Gr complying to the specifications of IS 269-2015 [59] was used in this study. Specific gravity of the OPC was 3.12 and Blaine's fineness was 350m^2/kg. Particle size of OPC was $D_{10}=6.9$ µm, $D_{50}=28.2$ µm and $D_{90}=61.6$ µm.

3.2 GGBFS

GGBFS was procured from near by reputed ready mix concrete plant and used in this study. GGBFS was confirming to IS 16714:2018 [60]. Specific gravity of GGBFS was 2.91 and Blaine's fineness 400 m^2/kg. Particle size of GGBFS was $D_{10}=2.4$ µm, $D_{50}=106.5$ µm and $D_{90}=560.4$ µm.

3.3 Metakaolin (MK)

MK, obtained from local supplier, complying to IS 16354:2015[61] was used in this study. MK's specific gravity was 2.24. Particle size of MK was $D_{10}=1.4$ µm, $D_{50}=7.1$ µm and $D_{90}=13.4$ µm.

3.4 Alkali resistant fibre (ARF)

ARF used in this study was procured from reputed manufacture. AR fibre 's diameter was 15 µm, length 15 mm, specific gravity was 2.6.

3.5 Polypropylene fibre (PPF)

PPF used in this study was procured from locally. PPF 's diameter was 25microns, length 12 mm, specific gravity was 0.9.

3.6 Coarse and fine aggregates

Crushed angular granite coarse aggregate (CA) 10 mm size and natural river sand having a powder content (< 125 µm) of 5% was used in this study. Coarse aggregate's specific gravity and water absorption was 2.78 and 0.6% respectively. Fine aggregate's specific gravity, water absorption was 2.63 and 1.2% respectively and fine aggregate was conforming to zone-III as per IS 383:2016 [62] and were complying with the requirements above specification requirement.

3.7 Water

Municipal supply tap water confirming to IS 456:2000 [63] was used in proportioning the SCC and HyFSCC mixes.

3.8 Super-plasticizer (SP)

Reputed brand high range water reducing admixture (HRWRA), PCE based, complying to IS 9103 [64] having a water reduction capacity of 34% was used in this study. SP's specific gravity was 1.13.

Material characteristics of OPC, GGBFS, MK is presented in Table 1. Particle size distribution (PSD) of OPC 53Gr, GGBFS and MK is presented in Fig. 1 and Scanning Electron Microscope (SEM) images of the same at 1 µm magnification is presented in Fig. 2.

3.9 Concrete mixing, samples casting and samples curing

$SCC_{control}$, $HyFSCC_{Type-1}$ and $HyFSCC_{Type-2}$ concrete mix proportion is presented in Table 2. $SCC_{control}$ and HyFSCC method of mixing followed, specimen sizes, shapes, is presented in Fig. 3.

4 Results and discussions

4.1 Fresh state properties of SCC and HyFSCC

Water demand of concrete mix prepared with GGBFS, as partial replacement of OPC, reduces when compared to water demand of the concrete mix prepared without any such replacements. While on the other hand for producing the SCC mixes with reactive SCM's like MK, as part replacement of OPC, water demand increases when compared to water demand of the concrete mix prepared without any such replacements. This is because of more

Table 1 Material characteristics of OPC, GGBFS, MK

Chemical compounds	OPC 53Gr	GGBFS	MK
CaO	63.08	36.20	–
SiO_2	22.39	33.77	53.40
Al_2O_3	4.88	16.61	42.10
MgO	4.35	12.28	15.79
Fe_2O_3	4.30	0.57	1.11
LOI	1.22	1.81	1.47
IR	3.09	2.14	1.93
Chloride	0.004	0.003	0.071
MnO	–	4.29	3.24
Specification	IS 269-2015	IS16714:2018	IS16354:2015

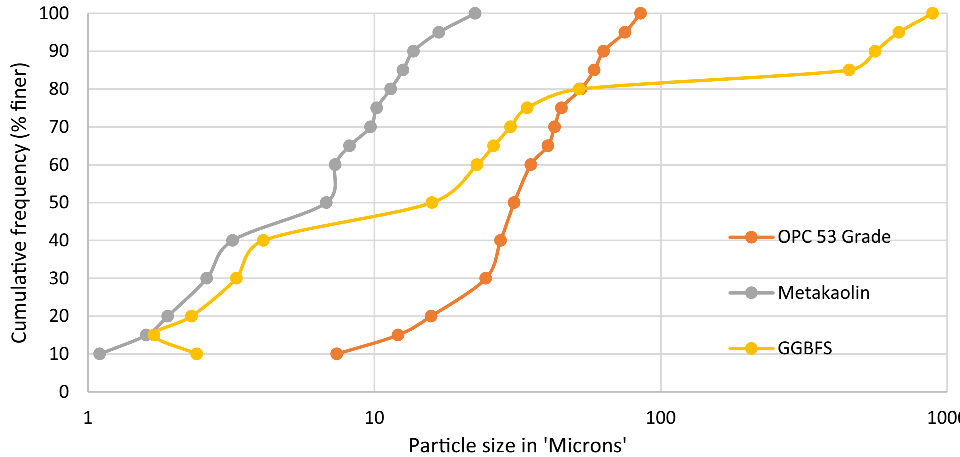


Fig. 1 Particle size distribution (PSD) of OPC 53 Gr, GGBFS and MK

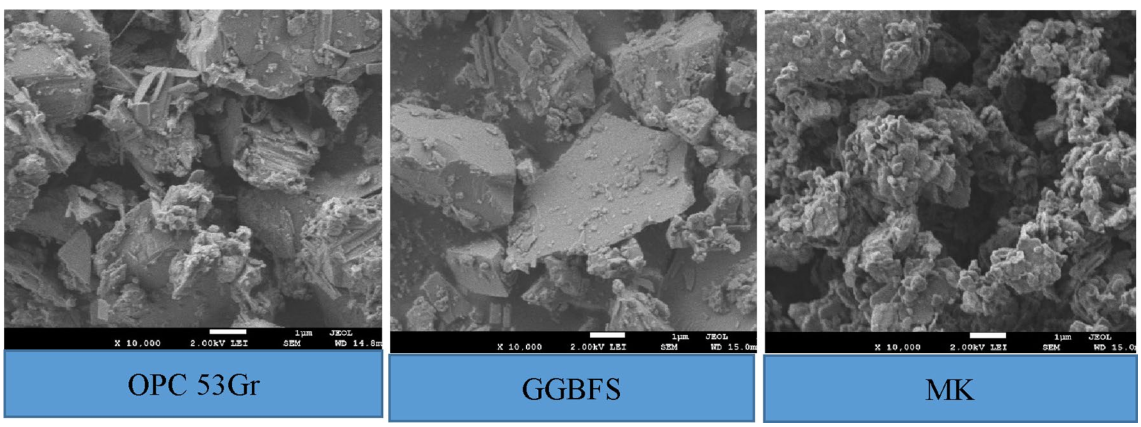


Fig. 2 SEM images of OPC 53 Gr, GGBFS and MK at 1 µm magnification

Table 2 SCC and HyFSCC mix proportions

Mix	Cementitious materials (CM) composition			Fibre composition by volumetric proportion		Materials for concrete (Kg/m^3)				
	OPC 53 Gr (%)	GGBFS (%)	MK (%)	PPF (%)	ARF (%)	Total CM	CA10mm	Sand	PCE admixture	Free water
$SCC_{Control}$	50	40	10	0	0	550	740	900	6.60	181.5
$HyFSCC_{Type1-A}$	50	40	10	1	0	550	740	900	6.60	181.5
$HyFSCC_{Type1-B}$	50	40	10	0.7	0.3	550	740	900	6.60	181.5
$HyFSCC_{Type1-C}$	50	40	10	0.6	0.4	550	740	900	6.60	181.5
$HyFSCC_{Type1-D}$	50	40	10	0.5	0.5	550	740	900	6.60	181.5
$HyFSCC_{Type2-A}$	50	40	10	0	1	550	740	900	6.60	181.5
$HyFSCC_{Type2-B}$	50	40	10	0.3	0.7	550	740	900	6.60	181.5
$HyFSCC_{Type2-C}$	50	40	10	0.4	0.6	550	740	900	6.60	181.5

fineness and increased surface area of MK [65]. Also, besides higher fineness of MK, increased surface area of overall cementitious materials like GGBFS and MK (in concrete) and chemical composition of MK demands more water as compared to concrete without any addition of MK to produce similar workable concrete. Further, incorporation of fibre in to the concrete mix also increases the water demand of concrete in producing the similar slump flow compared to concrete prepared without any fibre additions. This type of higher water demand of finer materials

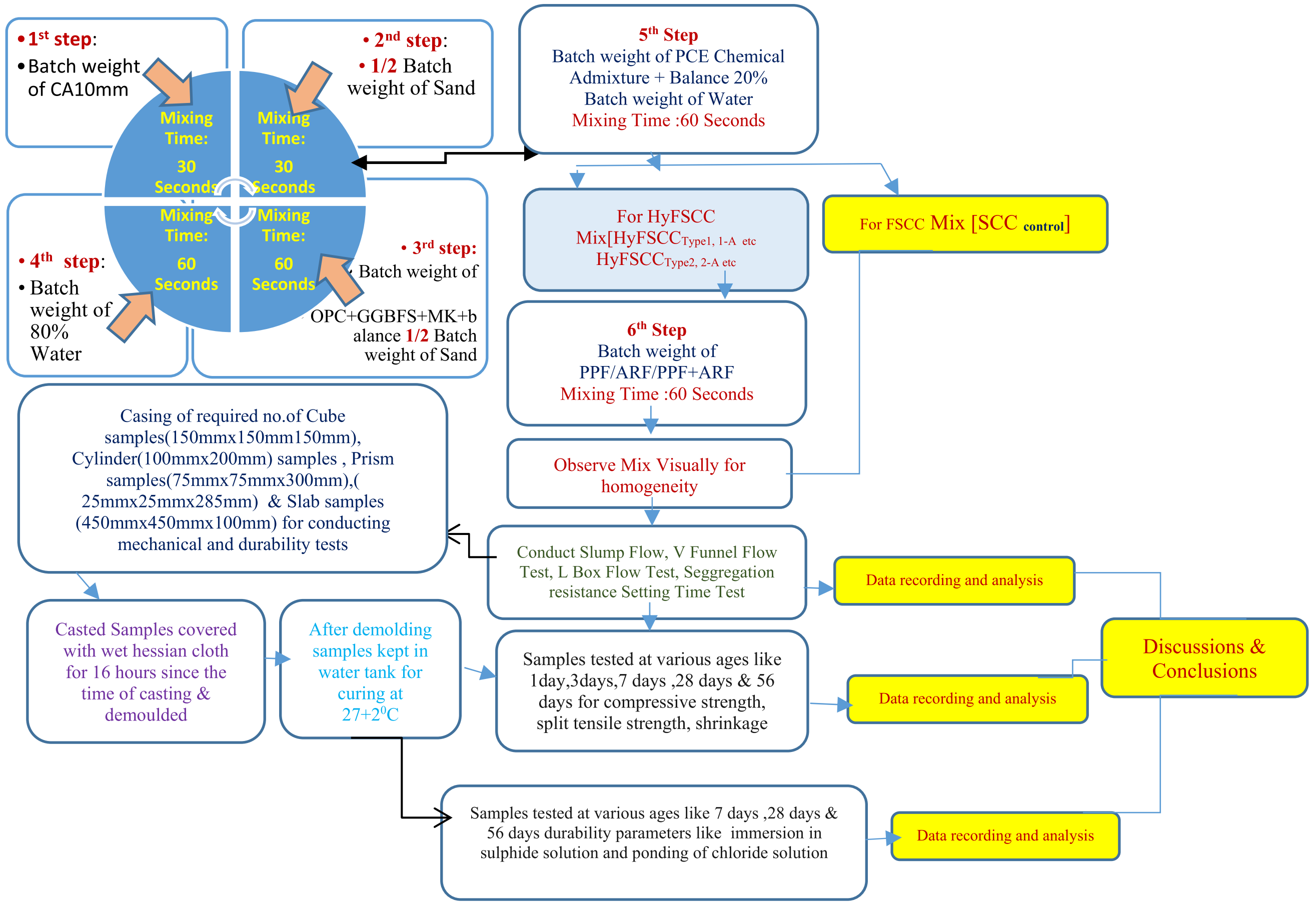


Fig. 3 SCC and HyFSCC mixing procedure in pan mixer, sample casting, curing, testing

can be compensated by using PCE based HRWA (capable of reducing water by 30–40%) chemical admixtures for preparing the concrete mixes [66–68]. Thus in this experimental study a total cementitious material content of 550 kg/m^3 (i.e. OPC + GGBFS + MK) was fixed and several trials of combinations of GGBFS and MK as part replacement of OPC was experimented at water/cementitious ratio of 0.33 to produce SCC$_{Control}$ mix meeting the slump flow requirement of SF1 (550–650 mm), and V funnel flow of class VF2 (9–25 s), segregation resistance of class SR1. Through laboratory trials and in accordance with [26, 52], it was established that a combination of 50% OPC + 40% GGBFS + 10%MK found to be suitable at PCE chemical admixture of 0.9% of cementitious material producing the SCC$_{Control}$ mix. Slump flow of SCC$_{Control}$ mix was 560 mm and V funnel flow was 22 s. When PPF and ARF fibres, in hybrid combinations (total 1%) by volume proportion, was added to the SCC$_{Control}$ mix, the slump flow reduced and was observed to be ranging from 430 to 460 mm. This reduction in slump flow was in agreement with the study [69]. Hence in order to achieve a targeted slump flow of 550–650 mm, the PCE chemical admixture dosage trials were conducted by increasing the PCE content from 0.95 to 1.30%, with an increment of 0.05% in each successive trial. Through these trials, it was observed that at 1.20% of PCE chemical admixture content the resulted HyFSCC$_{Type1}$ and HyFSCC$_{Type2}$ mixes were satisfying both the targeted slump flow as well as V funnel flow time. At 1.2% of PCE chemical admixture content the slump flow of SCC$_{Control}$ mix was 640 mm. This is reasonable that by the use of more PCE in the mixtures with less w/cm. This is in agreement with outcomes of other research studies [4, 6, 11]. The greater the slump flow, the superior will be the concrete to reach and fill each location of formwork. The increase in the cementitious system's fluidity due to the addition of PCE, promotes a decrease on the rheological constraints, as PCE adsorption on the particle's surface origins its deflocculation and parting off. In this means there is a higher comparative amount of water will be made available as lubrication in the cementitious system resulting more fluid ness to the matrix [11]. Fresh state properties of the SCC$_{Control}$ mix, various prepared

HyFSCC$_{Type1}$ and HyFSCC$_{Type2}$ mixes are discussed in the subsequent paras.

4.1.1 Slump flow

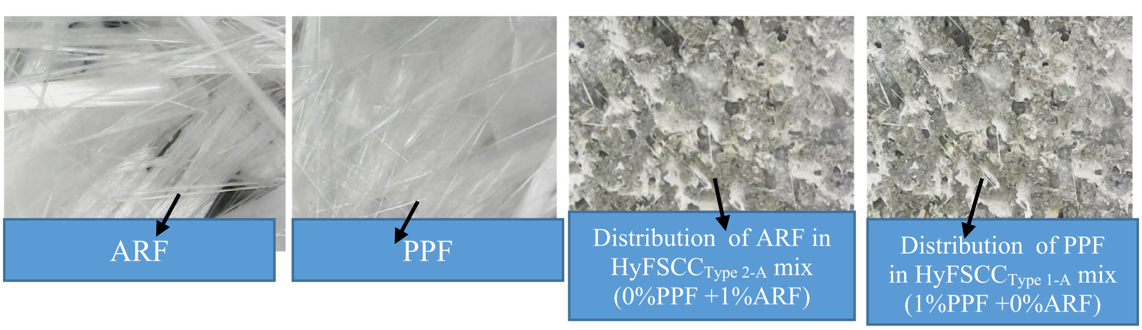
Slump flow of SCC$_{Control}$ mix and various HyFSCC mixes experimented in this study, variations in slump flow with reference to % of PPF, %ARF and several combinations of % PPF + % ARF, is presented in Fig. ***5. As can be seen from the Fig. ***5 that, the slump flow of SCCControl mix was higher (640 mm) when compared to the slump flow of HyFSCC$_{Type1}$ mix (with %PPF varied from 0 to 1.0%) and HyFSCC$_{Type2}$ mix (with ARF varied from 0 to 1%). The slump flow of HyFSCC$_{Type1}$ mix was reduced from 6.25 to 12.5% as the %PPF increased from 0 to 1%, whereas for HyFSCC$_{Type2}$ mixes -the slump flow was reduced from 9.38 to 12.5% as % ARF varied from 0 to 1%. These results are fairly in agreement with the outcome of the study on hybrid combinations of synthetic and steel fibres on slump flow characteristics of concrete [11, 12, 15, 26]. In this present study it was observed that, the minimum slump flow was 560 mm for HyFSCC$_{Type\ 2\text{-}C}$ (i.e. at 0.5% PPF + 0.5% ARF), and maximum slump flow was 600 mm for HyFSCC$_{Type\ 1\text{-}A}$ mix (i.e. at 1%PPF + 0%ARF). This results affirmed to the outcome of the study wherein a maximum 13% reduction in slump flow, as compared to control mix, was observed when polyolefin fibre were admixed in the SCC [33, 37, 38]. The variance amongst the present outcomes of this study with the findings of [33, 37, 38], is reasonable due to the usage of altered size of fibre, w/cm and PCE in this research study. The slump flow of HyFSCC$_{Type\ 2\text{-}A}$ mix (i.e. at 0% PPF + 1%ARF) was 580 mm. The probable reason for more slump flow in case of only PPF integrated SCC mix may be due to better integration into the SCC mix by PPF than ARF, as observed through the photo micro graph (at 1000 × magnification), as presented in Fig. ***4 of both the mixes at above % integration.

4.1.2 V funnel flow time

V funnel flow time of SCC$_{Control}$ mix and various HyFSCC mixes experimented in this study, variations in V funnel flow time with reference to % of PPF, %ARF and several combinations of %PPF + %ARF, is presented in Fig. ***6. V funnel flow time of SCC$_{Control}$ mix was observed to be 12 s. This result is aligning with the outcome of the study [37, 38] wherein it was showcased that by means of the optimal quantity of 10% MK in concrete, enough viscosity was achieved for the SCC mix and thus prompting the mix to flow quickly through the contracted space like V funnel. In this present study, it was observed that, when compared to V funnel flow time of SCC$_{Control}$ mix, the flow time of HyFSCC$_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and HyFSCC$_{Type\ 2}$ mix (with ARF varied from 0 to 1%) increased. This increase in flow time is due to the presence of PPF and ARF fibres in various combinations in the mixes. The results achieved for V funnel flow time test, in this study, is mostly aligned with outcome established by [5, 35] but the only difference is that in the study [35] fibres of 60 mm length were used and beyond 0.5% volume fraction of polyolefin fibres in SCC. There was considerable increase in the blockage and hence resulting increased V funnel flow time of mix to pass through the V funnel. In this present study, the HyFSCC$_{Type1}$ mix resulted in increased V funnel flow time from 58.33 to 75.00% and the V funnel flow time for mixes of HyFSCC$_{Type2}$ was increased from 66.67 to 75.10%. The minimum V funnel flow time was 17 s for HyFSCC$_{Type\ 1\text{-}B}$ and HyFSCC$_{Type\ 1\text{-}C}$. Maximum V funnel flow time was 21 s for HyFSCC$_{Type\ 2\text{-}B}$ and HyFSCCType $_{2\text{-}C}$ (Figs. 4, 5, 6, 7).

4.1.3 L box obstruction flow ratio

L box obstruction flow ratio of SCC$_{Control}$ mix and various HyFSCC mixes experimented in this study, variations in L box flow ratio with reference to % of PPF, %ARF and several



(a) (b) (c) (d)

Fig. 4 Photo micro graphs at 1000X magnification

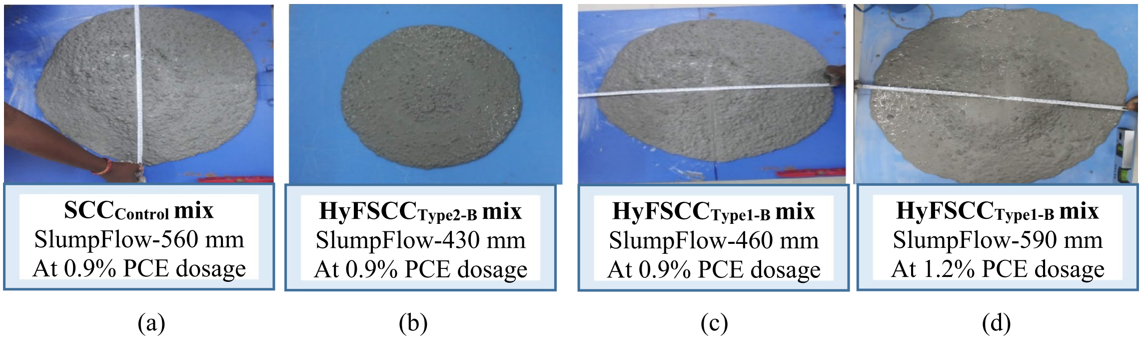


Fig. 5 Slump flow of $SCC_{Control}$, $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ mix

Fig. 6 Slump flow of SCC and HyFSCC mixes

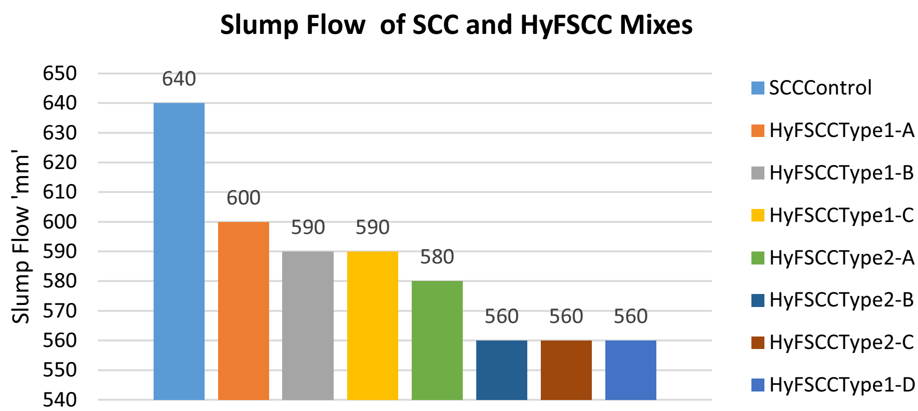
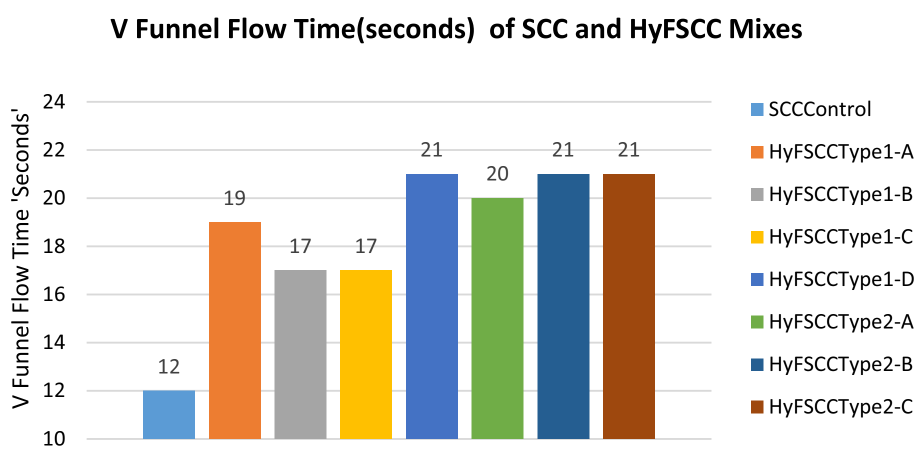


Fig. 7 V Funnel flow time of SCC and HyFSCC mixes



combinations of %PPF + %ARF, is presented in Fig. 7. L box obstruction flow ratio of $SCC_{Control}$ mix was 0.94. When compared to L box obstruction flow ratio of $SCC_{Control}$ mix, the L box obstruction flow ratio of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) reduced. This reduction in the L box obstruction flow ratio is due to the presence of PPF and ARF fibres in various combinations in the mixes. These results are fairly agreeing with the outcome of study [39, 40] wherein the low L box obstruction flow ratio, as observed for the fibre incorporated SCC mix, was due the fibre end shape leading to fractional constraint of the effort of fresh concrete against flow [6, 8, 15–18, 39, 40]. In this present study it was observed that, compared to L box obstruction flow ratio of $SCC_{Control}$ mix, L box obstruction flow ratio of $HyFSCC_{Type\ 1}$ reduced from 8.51 to 11.70% and the L box obstruction flow ratio for mixes of $HyFSCC_{Type\ 2}$ was reduced from 10.64 to 12.77%. The minimum L box flow ratio was 0.82for $HySCC_{Type2\text{-}A}$ and $HySCC_{Type2\text{-}C}$. Maximum L box flow ratio was 0.87 for $HyFSCC_{Type\ 1\text{-}C}$.

4.1.4 Segregation resistance (SR) %

SR (%) of $SCC_{Control}$ mix and various HyFSCC mixes experimented in this study and variations in SR with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in Fig. 8. SR of $SCC_{Control}$ mix was 15%. When compared to SR of $SCC_{Control}$ mix, the SR of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) increased. This increase in SR is due to the presence of PPF and ARF fibres in various combinations in the mixes. These results are in contrast to the results of the outcome of [21, 24] wherein it was mentioned that for achieving the same slump flow, as of control mix, the addition of steel fibres of one type not at all affected the water demand of the mix. Though, addition of other smaller diameters and sizes of steel fibres in to the mix, demand of water was reduced for fluidizing the matrix. The contrast of present study result with the study [21, 24] results may be due to the reasons of material nature of ARF and PPF fibres which requires more water than the steel fibres for maintaining the same slump flow in the mix. In this present study, it was observed that when compared to SR of $SCC_{Control}$ mix, SR of $HyFSCC_{Type\ 1}$ increased from 20.00 to 26.67% and the SR for mixes of $HyFSCC_{Type\ 2}$ was increased from 6.67 to 20.05%. The minimum SR was 16% for $HySCC_{Type2\text{-}B}$ and $HySCC_{Type2\text{-}C}$. Maximum SR was 19 for $HyFSCC_{Type\ 1\text{-}D}$.

4.1.5 Initial setting time (IST)

IST of $SCC_{Control}$ mix and various HyFSCC mixes experimented in this study and variations in IST with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in Fig. 9. IST of $SCC_{Control}$ mix was 480 min. When compared to IST of $SCC_{Control}$ mix, the IST of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) reduced. This reduction in IST is due to the to the presence of PPF and ARF fibres in various combinations in the mixes besides the reasons of fast reactions of MK due to its fineness and higher contents of Al_2O_3. These results are in fair agreement with the outcome of the study [42, 44]. I this present study it was observed that when compared to $SCC_{Control}$ mix, the IST of the resulted mixes of $HyFSCC_{Type\ 1}$ decreased from 8.73 to 16.67% and the IST for mixes for $HyFSCC_{Type\ 2}$ was decreased from 4.17 to 8.33%. The minimum IST was 400 min for $HySCC_{Type1\text{-}D}$. Maximum IST was 460 min for $HyFSCC_{Type\ 2\text{-}A}$.

4.1.6 Final setting time (FST) test

FST of $SCC_{Control}$ mix and various HyFSCC mixes experimented in this study and variations in FST with reference to % of PPF, %ARF and several combinations of PPF + ARF is presented in Fig. 10. FST of $SCC_{Control}$ mix was 580 min. When compared to FST of $SCC_{Control}$ mix, the FST of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) reduced. This reduction in FST is due to the to the presence of PPF and ARF fibres in various combinations in the mixes besides the reasons of fast reactions of MK due to its fineness and higher contents of Al_2O_3 [16, 19]. In this present study, it was observed that when compared to FST of $SCC_{Control}$ mix, the FST of $HyFSCC_{Type\ 1}$ reduced from

Fig. 8 L box flow ratio of SCC and HyFSCC mixes

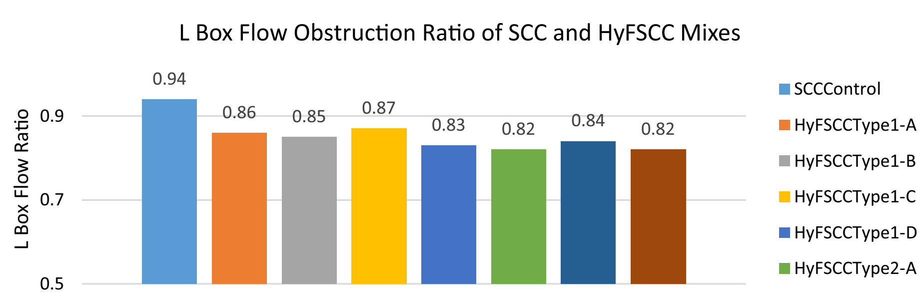
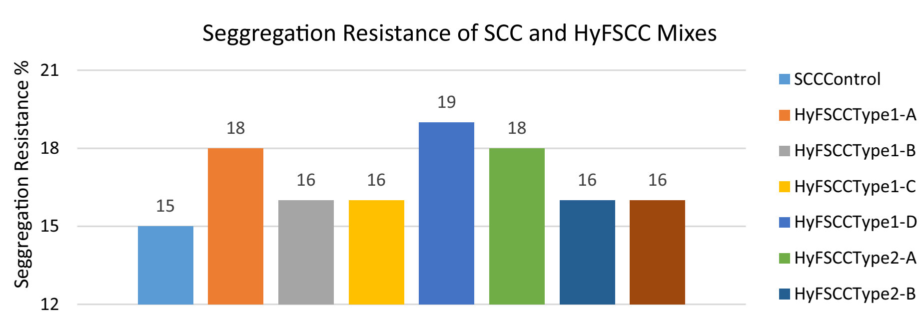


Fig. 9 Segregation resistance of SCC and HyFSCC mixes



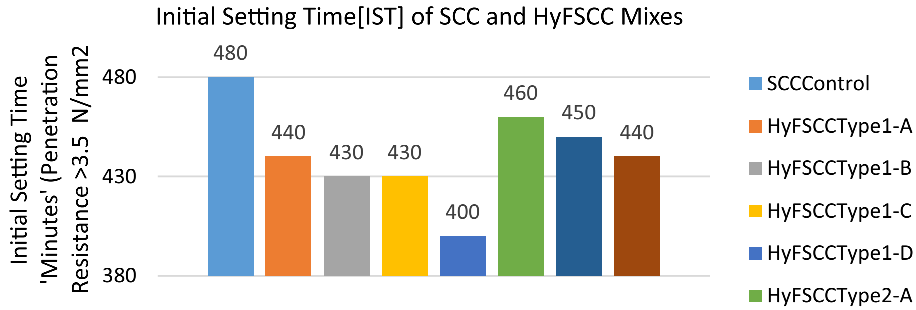


Fig. 10 IST of SCC and HyFSCC mixes

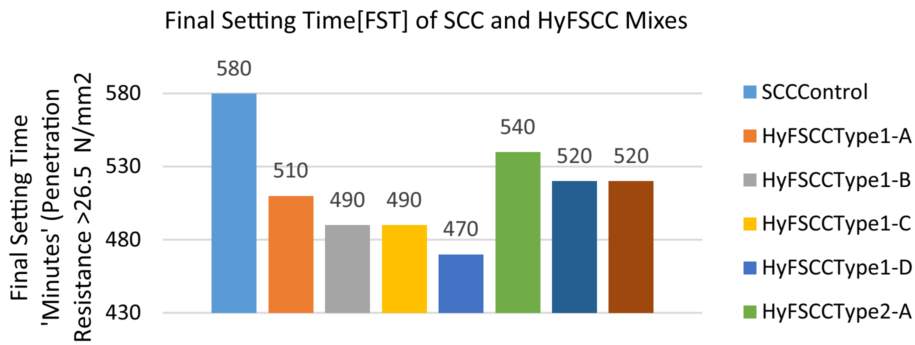


Fig. 11 FST of SCC and HyFSCC mixes

Table 3 Compressive strength of SCC and HyFSCC mixes

Mix ID	Compressive strength (N/mm^2)				
	1 Day	3 Days	7 Days	28 Days	56 Days
$SCC_{Control}$	24.10	33.20	54.80	58.70	59.60
$HyFSCC_{Type1\text{-}A}$	25.60	36.10	56.20	66.20	70.20
$HyFSCC_{Type1\text{-}B}$	26.20	38.20	56.80	66.90	70.60
$HyFSCC_{Type1\text{-}C}$	26.40	38.40	60.20	67.50	70.90
$HyFSCC_{Type1\text{-}D}$	26.70	39.40	60.90	67.90	71.40
$HyFSCC_{Type2\text{-}A}$	26.70	39.60	58.60	68.20	71.80
$HyFSCC_{Type2\text{-}B}$	27.10	40.40	59.20	68.90	72.60
$HyFSCC_{Type2\text{-}C}$	27.00	41.10	61.10	69.40	72.80

12.07 to 18.97% and the FST for mixes of HyFSCC $_{Type\ 2}$ was reduced from 6.30 to 10.34%. The minimum FST was 470 min for $HySCC_{Type1\text{-}D}$. Maximum FST was 540 min for $HyFSCC_{Type2\text{-}A}$ (Fig. 11).

4.2 Hardened state properties of SCC and HyFSCC

4.2.1 Compressive strength test

$SCC_{Control}$ mix and various HyFSCC mixes experimented in this study were tested for compressive strength at various ages like 1 day, 3 days, 7 days, 28 days and 56 days. Variations in compressive strength of the $SCC_{Control}$ mix and various HyFSCC mixes with age, with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in Table 3. The compressive force on the specimen was stopped on noticing the initial crack fine hairline in appearance. At 1 day the compressive strength of $SCC_{Control}$ mix was 24.10 N/mm^2. When compared to compressive strengths of $SCC_{Control}$ mix, the compressive strengths of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) increased for all the ages of test. The 1-day compressive strength of the resulted mixes of $HyFSCC_{Type\ 1}$ increased from 6.22 to 10.79% and the1 day compressive strength for mixes of HyFSCC $_{Type\ 2}$ was increased from 10.80% to 12.03%. The 1 day minimum compressive strength was 25.60 N/mm^2 for $HySCC_{Type1\text{-}A}$ and the maximum was 27.00 N/mm^2 for $HySCC_{Type2\text{-}C}$. All the experimented mixes of $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ were meeting the target 1 day compressive strength of 25.00 N/mm^2 as well as the targeted mean strength of 58.25 N/mm^2 at 28 days. Compressive strength of all the mixes were gradually observed to be increased from 1 to 56 days. Compressive strength gain of all the mixes with age was swifter during the ages of 1–3 days and later on the gain in compressive strength was slower for the ages of 7–56 days. This is because of the presence of MK in the mix which reacts quickly during the hydration reactions and also due to MK's chemical composition having higher content of Al_2O_3, higher fineness and greater surface area [41, 47]. $HySCCType_{1\text{-}D}$ i.e. mix consisting 0.5%PPF + 0.5%ARF marginally exhibited satisfactory mix and 1–56 days compressive strength. The failure patterns of the specimens were observed to be satisfactory and the same is presented in Fig. 12.

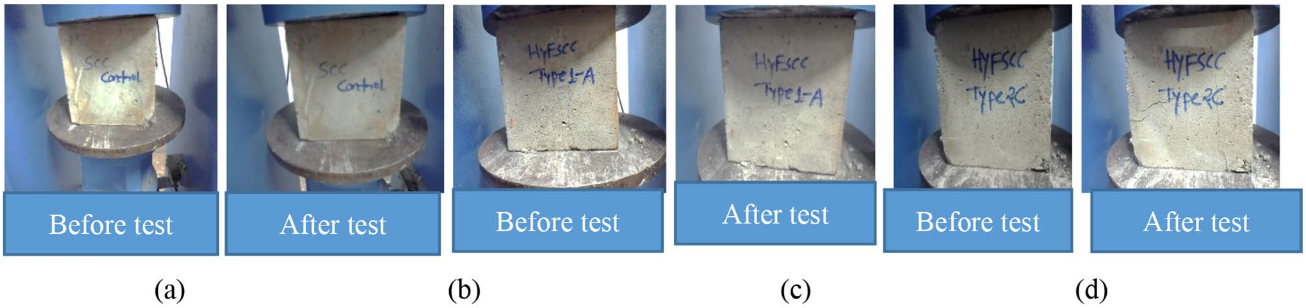


Fig. 12 Compressive strength test of SCC and HyFSCC mixes

Table 4 Split tensile strength (SPS) of SCC and HyFSCC mixes

Mix ID	Split tensile strength (SPS) (N/mm^2)				
	1 Day	3 Days	7 Days	28 Days	56 Days
$SCC_{Control}$	1.8	1.91	2.17	5.22	5.37
$HyFSCC_{Type1-A}$	2.1	2.18	2.42	5.38	5.41
$HyFSCC_{Type1-B}$	2.3	2.42	2.44	5.41	5.44
$HyFSCC_{Type1-C}$	2.3	2.44	2.47	5.43	5.44
$HyFSCC_{Type1-D}$	2.4	2.47	2.51	5.46	5.48
$HyFSCC_{Type2-A}$	2.3	2.42	2.54	5.46	5.72
$HyFSCC_{Type2-B}$	2.2	2.43	2.56	5.44	5.68
$HyFSCC_{Type2-C}$	2.2	2.46	2.56	5.42	5.69

4.2.2 Split tensile strength (SPS)

$SCC_{Control}$ mix and various HyFSCC mixes experimented in this study were tested for SPS at various ages like 1 day, 3 days, 7 days, 28 days and 56 days. Variations in SPS of the $SCC_{Control}$ mix and various HyFSCC mixes with age, with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in Table 4. At 1 day, the SPS of $SCC_{Control}$ mix was 1.80 N/mm^2. When compared to SPS of $SCC_{Control}$ mix, the SPS of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) increased for all the ages of test. SPS of $HyFSCC_{Type\ 1}$ increased from 16.67 to 33.33% and the SPS for mixes of $HyFSCC_{Type\ 2}$ was increased from 22.22 to 27.78%. This is because of the presence of ARF and PPF fibres in various hybrid combinations. The 1 day minimum SPS was 2.10 N/mm^2 for $HySCC_{Type1-A}$. For $HySCC_{Type2-D}$, the SPS was 2.4 N/mm^2 and it was observed to be the maximum amongst all the experimented mixes. All the mixes of $HyFSCC_{\ Type1}$ and $HyFSCC_{\ Type2}$ were meeting the target 1 day SPS of 2.00 N/mm^2. The failure patterns of the specimens tested for SPS was observed to be satisfactory and the same is presented in Fig. 13. SPS of all the mixes were gradually observed to be increased from 1 to 56 days. SPS gain of all the mixes with age was swifter during the ages of 1–3 days and later on for the ages of 7–56 days, the gain in SPS was slower. This was because of the presence of MK in the mix which reacts quickly during the hydration reactions and also due to MK's chemical composition having higher content of Al_2O_3, higher fineness and greater surface area [41, 47]. The present study demonstrates the surge in SPS and is in contrast with the outcome of study of MK's performance in conventional concrete containing [12, 19]. This may be due to the synergetic effect of MK and GGBFS in the cementitious system producing dense micro structure and thus refining the pore structure of the matrix. This can be seen in the Fig. 13 where in SEM images of hardened mortar matrix retrieved from the specimen after

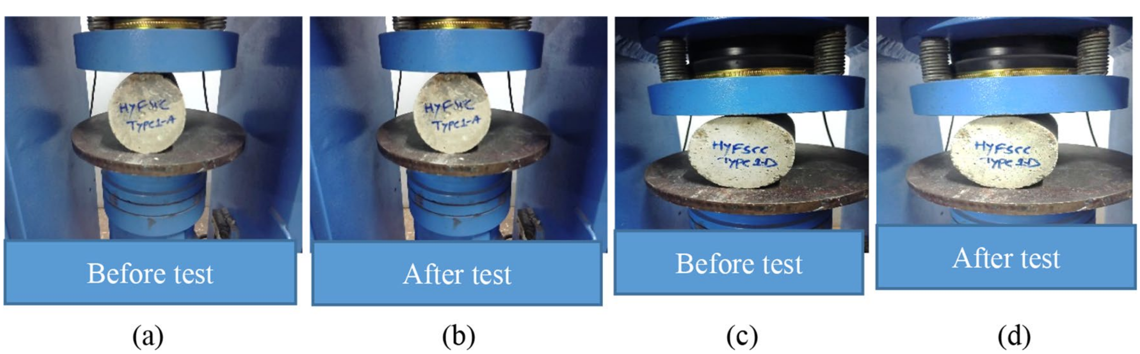


Fig. 13 Split tensile strength (SPS) test of SCC and HyFSCC mixes

the SPS at 3 days and 7 days of $HySCC_{Type1-D}$ i.e. mix consisting 0.5%PPF + 0.5%ARF. $HySCC_{Type1-D}$ mix marginally exhibited satisfactory mix and 1–56 days SPS. This results are in an analogous inclination to the outcome of observed enhanced test results of SPS in the SCC mix prepared with 10–15% MK [16, 17]. But only contrast of the present study is that during 7–28 days the SPS was substantially changed against the 28–56 days SPS. This is because the quicker hydration reaction of ultrafine MK in the early ages up to 7 days and later on due to the secondary hydration reactions of GGBFS till 28 days. Beyond 28 days the marginal increase in SPS may be attributed to the near ceasing of hydration reactions in the experimented mixes (Fig. 14).

4.2.3 Shrinkage (linear)

$SCC_{Control}$ mix and various HyFSCC mixes experimented in this study were tested for shrinkage (linear i.e. change in length of specimen), at various ages like 1 day, 3 days, 7 days, 28 days and 56 days. Variations in shrinkage of the $SCC_{Control}$ mix and various HyFSCC mixes with age, with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in Table 5. At 1 day, shrinkage of $SCC_{Control}$ mix was (−) 0.011. When compared to shrinkage of $SCC_{Control}$ mix, the shrinkage of $HyFSCC_{Type\ 1}$ mix (with %PPF varied from 0 to 1.0%) and $HyFSCC_{Type\ 2}$ mix (with ARF varied from 0 to 1%) reduced for all the ages of test. Shrinkage of $HyFSCC_{Type\ 1}$ mix, for the tested ages, decreased from 18.20% to 54.50% and the shrinkage for mixes of HyFSCC $_{Type\ 2}$ was decreased from 27.30% to 63.60%. The 1-day minimum shrinkage was (−) 0.004 for $HySCC_{Type1-D}$ and the maximum shrinkage was (−) 0.008 was for $HySCC_{Type1-B}$ and $HySCC_{Type2-A}$. Shrinkage of all the experimented mixes of HyFSCC $_{Type1}$ and HyFSCC $_{Type2}$ were gradually observed to be decreased from 1 to 56 days. Shrinkage of all the mixes was more during 1–3 days and later on for the ages of 7–56 days, the shrinkage was slower.

Table 5 Shrinkage of SCC and HyFSCC mixes

Mix ID	Shrinkage with reference to standard length gauge (−)				
	1 Day	3 Days	7 Days	28 Days	56 Days
$SCC_{Control}$	0.011	0.009	0.060	0.050	0.003
$HyFSCC_{Type1-A}$	0.009	0.008	0.008	0.005	0.002
$HyFSCC_{Type1-B}$	0.008	0.008	0.008	0.006	0.006
$HyFSCC_{Type1-C}$	0.006	0.006	0.006	0.006	0.006
$HyFSCC_{Type1-D}$	0.005	0.004	0.004	0.004	0.004
$HyFSCC_{Type2-A}$	0.008	0.007	0.007	0.007	0.007
$HyFSCC_{Type2-B}$	0.006	0.006	0.006	0.006	0.006
$HyFSCC_{Type2-C}$	0.004	0.003	0.003	0.003	0.003

This was because of the presence of MK in the mix which reacts quickly during the hydration reactions and also due to MK's chemical composition having higher content of Al_2O_3, higher fineness and greater surface area. Later on PPF and ARF fibres arrested the shrinkage because of nature of distribution of these fibres in the mix. These results are in alignment of the views disclosed in the study [36, 43] wherein the beneficiation effect of reduction of shrinkage of concrete was reported due to the presence of fibres in the ITZ space of concrete and the same can be seen through the photo micro graph as presented in the Fig. 4c, d. $HySCCType_{1-D}$ i.e. mix consisting 0.5%PPF + 0.5%ARF marginally exhibited less shrinkage from 1 to 56 days.

4.3 Durability tests on SCC and HyFSCC mixes

4.3.1 Expansion of specimen on immersion in sulphate solution

$SCC_{Control}$ mix and various HyFSCC mixes experimented in this study were tested, at various ages like 7 days, 28 days and 56 days, for expansion of specimens on immersion in

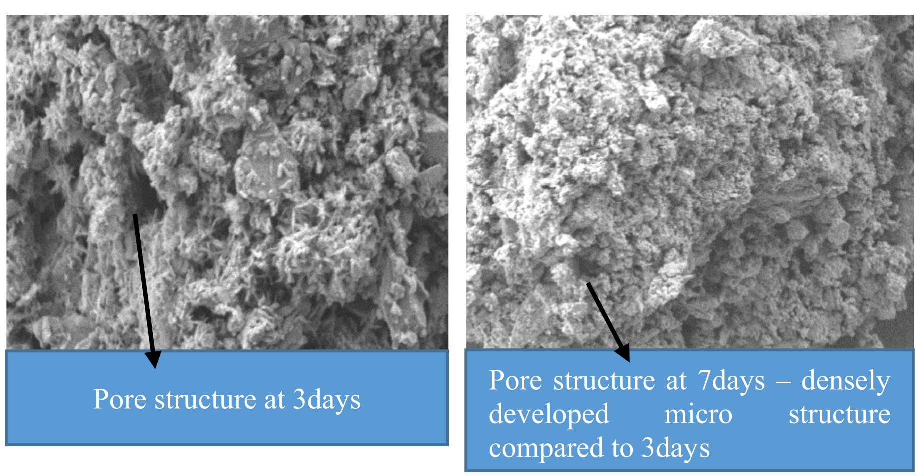


Fig. 14 SEM images at 1micron level of mortar (retrieved after SPS test) of $HyFSCC_{Type\ 1-D}$ mix at 3 days and 7 days

Na_2SO_4 (sulphate as SO_3^-) solution. The higher the expansion of specimen the lesser will be the resistance against ingression of sulphate ion. Variations in expansion of specimens of the $SCC_{Control}$ mix and various HyFSCC mixes with age, with reference to % of PPF, %ARF and several combinations of %PPF + %ARF presented in Table 6. The size of the specimen was 25mm × 25mm × 285mm and all the specimens were casted with the screened material passing through 4.75 mm sieve of the respective mix of $SCC_{Control}$ and various HyFSCC mixes. All the casted specimen were stored for 24 h in a humidity cabinet at controlled temperature of 27 °C ± 2 °C and relative humidity of at least 95%, After 24 h, all the specimens were taken out of humidity cabinet, demoulded, measured for initial length in the length comparator and immersed, for 7 days, 28 days and 56 days time, in Na_2SO_4 (sulphate) solution. The sulphate solution was prepared in a way such that each litre of solution shall contain 50.0 g of Na_2SO_4 dissolved in 900 ml of distilled water, and diluted with additional distilled or deionized water to obtain 1.0 l of solution. All the specimens immersed in sulphate solution were taken out carefully from the solution after 7 days, wiped carefully, measured for change in length in the length comparator and the specimen were carefully immersed again till the next measurement of 28 days and 56 days. In this study it was observed that, for $SCC_{Control}$ mix specimen, the expansion (i.e. change in length) was 0.008 mm with reference to measured length at 1 day. Compared to the expansion of specimens of $SCC_{Control}$ mix, the expansion of specimens of $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ mixes reduced during the all ages. Expansion of the specimen at The 7 days $HyFSCC_{Type\ 1}$ mixes decreased from 37.50 to 50.00% and the expansion of the specimen for mixes of $HyFSCC_{Type\ 2}$, was decreased from 62.50% to 75.00%. The 7 days minimum %expansion was 0.03 for the mixes $HySCC_{Type2\text{-}A}$, $HySCC_{Type2\text{-}B}$ and $HySCCType_{2\text{-}C}$. Maximum %change in length of the specimen was 0.04 for the mixes $HySCC_{Type1\text{-}A}$, $HySCC_{Type1\text{-}B}$ and $HySCC_{Type1\text{-}C}$. Expansion of all the specimens of experimented mixes of $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ observed to be decreased gradually from 7 to 56 days. At 7 days, expansion of the specimens of all the mixes was more and later on, for the ages of 28–56 days, the expansion of the specimens were slower.

Table 6 Resistance to sulphate ion ingression of SCC and HyFSCC mixes

Mix ID	% Length change of 25mm × 25mm × 285mm size specimens on immersion in sulphate solution		
	7 Days	28 Days	56 Days
$SCC_{Control}$	0.09	0.05	0.05
$HyFSCC_{Type1\text{-}A}$	0.08	0.06	0.06
$HyFSCC_{Type1\text{-}B}$	0.05	0.04	0.03
$HyFSCC_{Type1\text{-}C}$	0.05	0.04	0.03
$HyFSCC_{Type1\text{-}D}$	0.05	0.04	0.03
$HyFSCC_{Type2\text{-}A}$	0.04	0.04	0.03
$HyFSCC_{Type2\text{-}B}$	0.03	0.03	0.01
$HyFSCC_{Type2\text{-}C}$	0.03	0.03	0.01

This is because of the presence of MK in the mix reacting quickly during the hydration reactions and also due to MK's chemical composition of having higher Al_2O_3, higher fineness and greater surface area. Fineness of the MK will also help in pore refinement and which in turn offers resistance against penetration of foreign materials in to the body of the specimens. These results are agreeing with the views as stated in the study [13, 17]. During the periods beyond 7 days, PPF and ARF fibres were observed to arrest the change in length of the specimen because of nature of distribution of these fibres in the mix as verified through the photo micro graph presented in the Fig. 4c, d. Specimens of $HySCC_{Type2\text{-}C}$ i.e. mix consisting 0.5%PPF + 0.5%ARF marginally exhibited less expansion from 7 to 56 days.

4.3.2 Resistance to chloride (Cl^-) ion penetration

$SCC_{Control}$ mix and various HyFSCC mixes experimented in this study were tested, at various ages like 7 days, 28 days and 56 days, for Cl^- ion content in the concrete core specimens extracted at 7 days, 28 days and 56 days from the slab samples casted of mixes of $SCC_{Control}$ mix and various HyFSCC mixes. These slab samples were kept ponded with 3% NaCl solution. The concrete core samples of 25 mm diameter and 40 mm in length were extracted from above ponded slab samples at 7 days, 28 days and 56 days. These extracted core samples were crushed carefully in the mortar pestle, dried in hot air oven for 24 h to expel the moisture. These dried samples were screened through 150-μm size sieve to prepare the powder samples for analysis of Cl^- ion content. The higher the Cl^- ion content in the concrete, the lesser will be the resistance against ingression of Cl^- ion in the concrete. Variations in Cl^- ion content in concrete core specimens of the $SCC_{Control}$ mix and various HyFSCC mixes with age, with reference to % of PPF, %ARF and several combinations of %PPF + %ARF is presented in in Table 7. For $SCC_{Control}$ mix, the Cl^- ion content of the extracted concrete core specimen, at 7 days of ponding, was 0.009. Compared to the Cl^- ion content of extracted concrete core specimens of $SCC_{Control}$ mix, the Cl^- ion content of extracted concrete core specimens of $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ mixes, observed to be reduced during the all ages of ponding. Cl^- ion content of $HyFSCC_{Type\ 1}$ decreased from 33.33 to 44.45% and the Cl^- ion content for mixes of $HyFSCC_{Type\ 2}$ decreased from 11.10 to 22.20%. The minimum Cl^- ion content at 7 days age of ponding was 0.005 for

Table 7 Resistance to chloride ion ingression of SCC and HyFSCC mixes

Mix ID	% Cl^- at 40 mm depth Slab specimen ponded with chloride solution		
	7 Days	28 Days	56 Days
$SCC_{Control}$	0.009	0.006	0.005
$HyFSCC_{Type1-A}$	0.006	0.004	0.003
$HyFSCC_{Type1-B}$	0.006	0.004	0.003
$HyFSCC_{Type1-C}$	0.005	0.004	0.003
$HyFSCC_{Type1-D}$	0.005	0.004	0.003
$HyFSCC_{Type2-A}$	0.007	0.003	0.002
$HyFSCC_{Type2-B}$	0.008	0.003	0.002
$HyFSCC_{Type2-C}$	0.008	0.003	0.002

$HySCC_{Type1-B}$. Maximum Cl^- ion content at 7 days age was 0.008 for $HySCC_{Type2-B}$ and $HySCC_{Type2-C}$ mixes.

Cl^- ion content of all the specimens of experimented mixes of $HyFSCC_{Type1}$ and $HyFSCC_{Type2}$ were gradually observed to be decreased from 7 to 56 days. Cl^- ion content of the specimen of all the mixes was more during 7 days and later on for the ages of 28–56 days, it was reduced gradually. This reduction in Cl^- ion content was because of the presence of MK in the mix which reacts quickly during the hydration reactions and also due to MK's chemical composition having higher Al_2O_3, higher fineness and greater surface area. Fineness of the MK will also help in pore refinement and which in turn offers resistance against penetration of foreign materials in to the body of concrete. These results are confirming with the outcome of the study [13, 17]. Presence of PPF and ARF fibres in the mix also improved the penetration resistance of the specimen because of nature of distribution of these fibres in the mix. Specimens of $HySCC_{Type1-D}$ i.e. mix consisting 0.5%PPF + 0.5%ARF marginally exhibited marginally uniform resistance to Cl^- ion penetration from 7 to 56 days.

5 Conclusions

This experimental study was designed to investigate various combinations of polypropylene fibre (PPF) and alkali resistance fibre (ARF) in a total hybrid fibre proportion of 1% by weight of total cementitious materials of 550 kg/m^3 in the proportioned HyFSCC mixes. Based on the fresh state tests, mechanical tests at various ages from 1 to 56 days and durability tests conducted from 7 to 56 days age the following conclusions are drawn:

1. For the HyFSCC mixes (consisting of total 1% hybrid fibre content), as the PPF content was reduced in association to ARF content, Slump flow reduced, V funnel flow time increased, L Box obstruction flow ratio reduced and segregation resistance increased as compared to $SCC_{Control}$ mix (without any fibre inclusions).
2. Initial setting time (IST) as well as final setting time (FST) increased in the HyFSCC mixes (consisting of total 1% hybrid fibre content), as the PPF content was reduced in association to ARF content,
3. Compressive strength and split tensile strength increased, for all the ages, in the HyFSCC mixes (consisting of total 1% hybrid fibre content), as the PPF content is reduced in association to ARF content.
4. $HyFSCC_{Type2-C}$ mix i.e. mix comprising of 0.4%PPF + 0.6%ARF, demonstrated marginally higher compressive strength and marginally lower split tensile strength as compared to $HyFSCC_{Type1-D\ mix}$ i.e. mix comprising of 0.5% PPF + 0.5%ARF.
5. All the experimented mixes of $HyFSCC_{Type1}$ and $HyFSCC_{Type\ 2}$ with 1% hybrid fibre combinations attained the targeted 1-day compressive strength target of 25 N/mm^2 and split tensile strength of 2.0 N/mm^2.
6. $HyFSCC_{Type2-C}$ mix (consisting of 0.4%PPF + 0.6%ARF) marginally performed well in terms of shrinkage resistance and durability against the expansion on immersion in sulphate solution (i.e. penetration against $SO3^-$ ions).
7. $HyFSCC_{Type1-D}$ (consisting of 0.5% PPF + 0.5%ARF) mix marginally performed well in terms of durability against penetration of Cl^- ions.

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Declarations

Conflict of interest Authors declare that they have no conflicts of interest.

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