



Properties of SCC containing pozzolans, Wollastonite micro fiber, and recycled aggregates



Shashi Kant Sharma*

Civil Engineering Department, National Institute of Technology Jalandhar, Punjab, 144011, India

ARTICLE INFO

Keywords:

Civil engineering
Concrete
Microsilica
Flyash
Wollastonite micro fiber
Recycled aggregates
Construction engineering
Concrete technology
Cement additive
Concrete structure
Cement

ABSTRACT

Self compacting concretes (SCC) containing higher volumes of pozzolanic materials possess compressive strengths up to 30MPa. Fibers like steel, polypropylene, and carbon fibers are added in small volumes ranging from 0.25-2% v/v of concrete to increase the strength (>40MPa) of such concretes as higher volumes of fiber cause balling effect on account of inhomogeneity, thereby reducing the strength and workability. Hence higher volume of cement substitution either with mineral admixtures or fibers, or with both, to increase strength and workability is limited in the case of SCC. The condition worsens further if recycled aggregates replace normal aggregates. Wollastonite micro fiber (WMF) is a promising material that could be used in higher contents but its interaction with recycled aggregates to affect workability and strength has not been studied. Therefore this study tries to obtain a high strength concrete (>M40) by use of WMF along with flyash @ 5%, maximally up to 10% each. Microsilica was added @ 2.5%, maximally up to 10% to improve the interphase strength and make the concrete homogeneous. Results indicated that in order to obtain a high strength mix for such composites, higher amounts of WMF ($\geq 10\%$ by weight of binder) such that WMF:flyash varies from 1:1 to 2:1 is required, along with microsilica contents $\geq 7.5\%$. Literature suggests 5% microsilica along with either 20% WMF or 10% flyash, for yielding high strength SCC without recycled aggregates. Hence use of nearly equal amounts of WMF, flyash, and microsilica such that nearly 30% of cement is substituted, is recommended.

1. Introduction

The substitution of cement in concrete has been a subject of research since the last quarter of the twentieth century. It was established that pozzolanic materials could substitute cement by nearly 20–30% without compromising the final strength of concrete, and also improve the durability of concrete. These materials have been found to densify the concrete (ACI, 1994) and improve the interfacial transition zone between mortar and aggregates to a big or small extent (Cohen et al., 1994; Khayat and Aitcin, 1992; Mehta, 1985) depending upon their physical and chemical properties. Apart from these advantages environment is also conserved as carbon dioxide emission rate is equivalent to the cement manufactured. Fibers are introduced in the concrete to increase its flexural toughness and resistance against impact loading, as fibers have the capability to absorb the stresses which prolong the crack formation (Ghugal, 2003; Gupta et al., 2008; Kalla et al., 2011; Kaushik et al., 1994; Pierre et al., 1999; Ransinchung and Kumar, 2010; Soliman and Nehdi, 2012). Also, fibers make the concrete more durable since abridged cracks mitigate the attack of moisture in the concrete. Microfibers have been

found to improve the interfacial transition zone between coarse aggregates and mortar (Krishnamoorthy and Kumar, 1994; Low and Beaudoin, 1992; Lawler et al., 2005). Fiber-reinforced concrete has its application as ultra-high-performance concrete overlays for rigid pavements that are subjected to cyclic loading. This study also tries to obtain a similar type of concrete, but with the use of recycled aggregates.

Recycled aggregates are expected to affect the workability and strength of concrete. RCA obtained from demolition wastes is composed of natural coarse aggregates and adhered mortar that gives the aggregate skeleton properties of reduced density, higher water absorption, greater angularity and rougher surface texture (Zhan et al., 2013; Taboada et al., 2016; Assaad and Daou, 2017). This hinders the flow of concrete. Though workability could be improved with the use of superplasticizers but the rate of slump loss over time increases with RCA additions because of the higher absorption of water from the pore solution (Tang et al., 2016; Faleschini et al., 2014; Assaad, 2017; Matar and Assaad, 2017). It was also found that RCA increases the static stability of SCC i.e. segregation resistance and bleeding due to the absorption of free water in concrete. Hence it would not be wise to reject the use of RCA in SCC.

* Corresponding author.

E-mail address: shashi.pec@gmail.com.

RCA exhibit low abrasion resistance, therefore it is possible that the concrete could exhibit high deterioration against wearing action of moving loads. Concrete containing only recycled aggregates have lesser strengths as these aggregates are weaker than their normal counterparts and also the interfacial transition zone around these aggregates is known to be weaker and thicker than ITZ around normal aggregates (Kumar and Kaushik, 2004; Larbi, 1993). High water absorptivity and weak physical configuration (containing voids) are the two main factors responsible for this effect (Abed et al., 2018; Santos et al., 2019; Thomas et al., 2019). If only the voids in the interface are refined and reinforcing links between aggregates and mortar are established, the strength of ITZ could be improved (Bentz et al., 1992). Fibers hinder the flow of concrete due to their clumping (called as the balling effect) and higher interactions with coarse aggregates. There exists a critical fiber concentration (Martinie et al., 2010; Mehdipour et al., 2013) above which the concrete could not flow even if it's a SCC. This limit may fall more in case of concrete made of RCA. Matar and Assaad (2017) concluded that polypropylene fibers when used along with RCA, dramatically curtailed the flow properties of a SCC and also could not improve the strength. Roughness introduced by fibers also may increase the abrasion loss of concrete. This drop-in property could be mitigated by the use of polymeric latexes which have been found to improve the workability and strength of concrete based on increased bond strength at the interface and increased shear strength. Though latex material could be used in concrete, it increases the cost of concrete and also does not solve the purpose of high cement substitution as very low volumes (1–3%) of these materials are used. Pozzolanic materials are known to increase the workability and make the concrete smooth due to pore size and grain size refinement carried over by them in between the voids of cement particles.

Hence the present study aims to utilize pozzolanic materials to mitigate the limitations of recycled aggregates and fibers in yielding a SCC, which should have a flexural strength ≥ 4.5 MPa and abrasion-resistant quality. Fibers, on the other hand, shall complement pozzolanic materials in achieving the desired strength of concrete. Self flowing capability in pavement concrete is a boon as it reduces the construction period and effort. Also, SCC ensures higher mortar volume around recycled aggregates thereby giving full chance for bonds to develop between old mortar and ITZ, and also between ITZ and new mortar. Flyash has been used in this study which is obtained as surplus industrial waste material and is not even good for health if dispersed in the air. Naturally occurring Wollastonite micro fiber (WMF) which is an acicular micro fiber composed of calcium-meta-silicate such that calcium oxide and silica are present in equal proportions (nearly 45%) (Ransinchung and Kumar, 2010; Ransinchung et al., 2009), has been used. This has been done as the literature suggests that this microfiber is also pozzolanic and could be used in higher amounts to substitute cement without compromising the strength of concrete. Aggregate gradation with a nominal maximum size of 16mm was obtained from the demolition of older concrete pavement

which had none signs of alkali-silica reactivity, leaching or sulphate reaction. It was also decided to use microsilica as a cement substitute because literature has suggested that the strength of the interfacial transition zone is improved to a higher extent by the use of this material.

2. Methodology

2.1. Materials and mixes

Ordinary Portland cement (OPC) 43 grade was used in the study. Graded river sand conforming to Zone-II having fineness modulus of 3.23 and a specific gravity of 2.58 was used as fine aggregate. Recycled coarse aggregates of 20 mm MSA and 10mm MSA were used in the proportion of 60:40 to yield aggregates of MSA 16mm (Fig. 1). The specific gravity values of 20 mm and 10 mm aggregates were 2.32 and 2.39 respectively. Also, their impact, abrasion, crushing strength and water absorption values were 24%, 36%, 31%, and 2.5%, respectively. Flakiness & elongation index values were quite higher at 25.5% & 15.3%. The angularity number of aggregates at 10.6% represented sharp edges amongst them. Fine amorphous wollastonite micro fiber supplied by Rajwara Stonex Limited was used. It had a specific surface and specific gravity values of 827 m²/kg and 2.9 respectively. Needle shaped microfibers, having an average length and diameter of 30 microns and 1.4 micron respectively were used, which indicates that the microfiber have an approximate aspect ratio of 21:1 (Fig. 1). Dey et al. (2015) confirm that the fiber generally possesses an aspect ratio ranging from 3:1 to 20:1. Densified 920D grade Microsilica supplied by India Private Limited was used. It had a specific surface and a specific gravity value of 18000 m²/kg and 2.05. Fig. 2 shows the particle size distribution of powdery materials. High water reducing polycarboxylate ether (PCE) based superplasticizer: Master Glenium SKY 8233 was used to introduce self-compacting workability conditions to the concrete. It is free of chlorides and has low alkali content.

Fourteen mixes were constituted from these materials with a maximum cement substitution level of 30%. Both WMF and flyash substituted cement at 5% and 10% each, such that the ratio of their weights ranged from 1/2: 1 to 2:1. Microsilica was added in such a way that its content did not exceed either of WMF or flyash content of the specific mix. The intention was to fill the voids in between cement particles with WMF/flyash and likewise in between WMF/flyash with microsilica. Ransinchung and Kumar (2010) have suggested that microsilica can be used beneficially up to 7.5% to enhance the strength of concrete. Mix designation has been done in such a fashion that 5% of either WMF or flyash has been named as lower case "w" or "f". Similarly, 10% of each has been designated as upper case "W" or "F". Cement has been named as C. Microsilica has been named as S1, S2, S3, S4 depending upon its content level i.e. 2.5, 5, 7.5 or 10%. Hence, the fourteen mixes are C, Cwf, CwfS1, CwfS2, CWf, CWf, CwFS1, CwFS1, CwFS2, CwFS2, CWF, CWF, CWF, CWF.

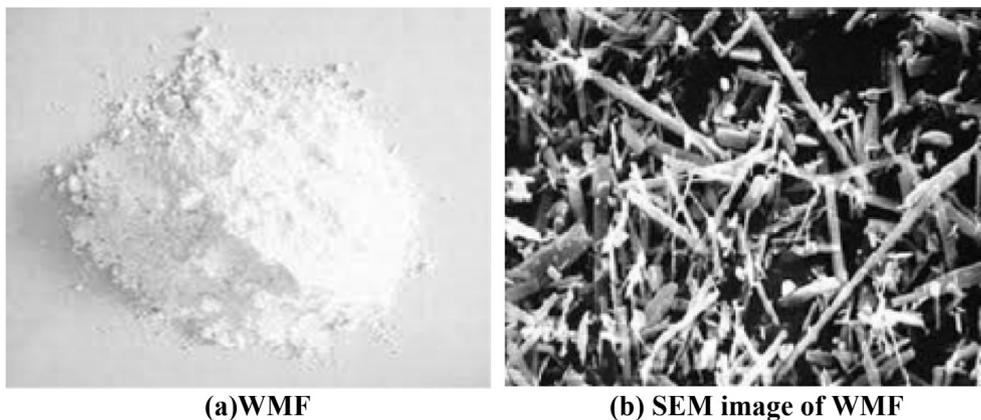


Fig. 1. WMF used in the study (left) and SEM image of WMF (right).

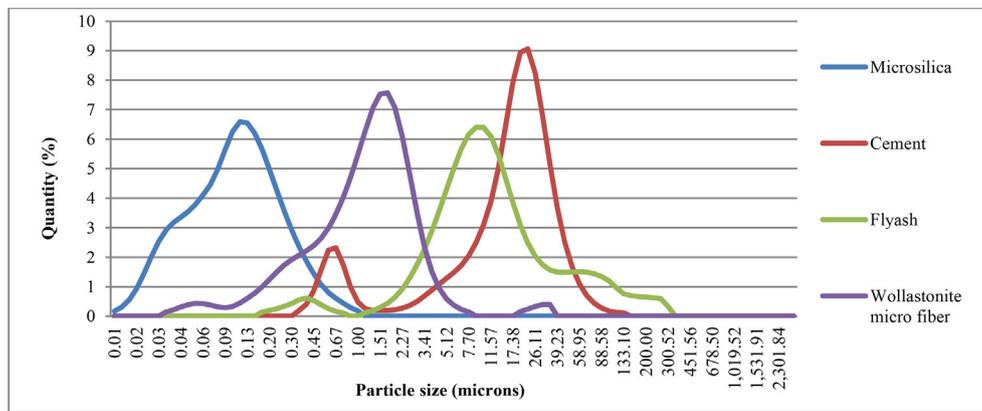


Fig. 2. Particle size distribution of cement and supplementary cementitious materials.

CWFS2, CWFS3 and CWFS4.

Normal pavement quality concrete with a W/C ratio of 0.36 and flexural strength of 4.5 MPa was designed as per IRC 44. It had cement, fine aggregate and coarse aggregate content of 450 kg/cum, 710 kg/cum and 1060 kg/cum, respectively which resulted in fine aggregate to a coarse aggregate ratio of 0.40. Trial combinations were constituted by substituting cement with additives such that the water to cementitious material ratio remained equal to water: cement ratio of normal concrete. This was done to avail a minimum amount of water to the mixes and that too for either primary or secondary hydration and not for the flow of admixtures. PCE was added by the weight of cement content ranging from 0.45-0.90% in all mixtures to compensate for the excessive water requirement for inducing flow. Trials were performed by checking workability after cement substitution, followed by successive increments in fine aggregate: coarse aggregate ratio by an interval of 5% to bring the workability at par with a SCC. It was found during the trials that ternary mixes, quaternary mixes with 5% microsilica, and quaternary mixes with 10% microsilica required a fine aggregate to a coarse aggregate ratio of 55:45, 50:50 and 45:55, respectively. This also justifies the use of higher amounts of microsilica, as very little variation in this ratio is required which makes the design closer to that of a normal mix.

2.2. Tests conducted

All of the concrete mixes were tested first for self-compacting ability via Abrams cone & V funnel flow test, J Ring passing ability test, and V funnel & probe ring segregation test as per EFNARC guidelines (EFNARC, 2002, 2005). Afterward, compressive strength was evaluated at 7, 30, 60 and 90 days curing as per IS 516. The flexural strength test was also performed on these mixes as per the same code after 28 days of curing. Finally, all the mixes were subjected to abrasion resistance test as per IS: 9284-1979 (sandblast method) in which an abrasive sand charge (4000g), passing 1mm and retained on 0.5 mm sieve is stroked on a 10 cm × 10 cm × 10 cm cubic concrete specimen. A pneumatic hollow needle with an arrangement for a striking charge from a height of 50 mm, with an air pressure of 0.14 N/mm² was used (Fig. 3).

3. Results

3.1. Flowing ability

Fig. 4 shows the flow time results for various concrete mixes through Abram's Cone, which is proportional to the flowing ability. EFNARC guidelines specify that a concrete having 600mm flow diameter possess flowing ability equivalent to a self-compacting concrete. Results show that almost all concrete mixes showed good flowing ability. Results from the test could be analysed in the form of following five flow trends which represent mixes and their corresponding workability in mm:



Fig. 3. Apparatus to evaluate abrasion resistance of concrete mixes.

$$\text{C-Cwf-CwF-CwF-CWF: } 380-580-550-590-550 \quad (1)$$

$$\text{Cwf-CwfS1-CwfS2: } 580-590-600 \quad (2)$$

$$\text{CwF-CwF1-CwF2: } 550-590-605 \quad (3)$$

$$\text{CwF-CwF1-CwF2: } 590-610-640 \quad (4)$$

$$\text{CwF-CwF1-CwF2-CwF3-CwF4: } 550-575-610-580-550 \quad (5)$$

The flowing ability of a mix depends upon two factors: viscous and frictional forces (Grunewald and Walraven, 2001). Viscous forces depend upon the cohesion of cement particles and the adhesion of admixture particles at their surfaces. The cohesive, as well as adhesive properties of a mix depend further upon two factors: physical & chemical properties of particles. Size of an admixture particle is the prominent physical property that affects the voids' distribution, and thus the contact of cement particles with each other, thereby affecting the cohesive forces amongst them. Finer particles get adsorbed over the surface of cement particles and bring repulsion or attraction between them depending upon the chemical charge carried by the latter. Microsilica and flyash carry a negative charge (Lei et al., 2016).

Frictional forces are controlled directly by the shape of the particles but the size of the particles indirectly controls it (Hossain et al., 2012). When the particles are not well graded, the voids in the mix increase which reduces the dominance of their shapes in altering the frictional forces. Microsilica is round and amorphous; the flyash is round and amorphous-glassy, whereas cement is angular and crystalline. The round and amorphous structure makes a particle flow exhibitor whereas angular crystalline structure inhibits the flow. WMF being acicular and

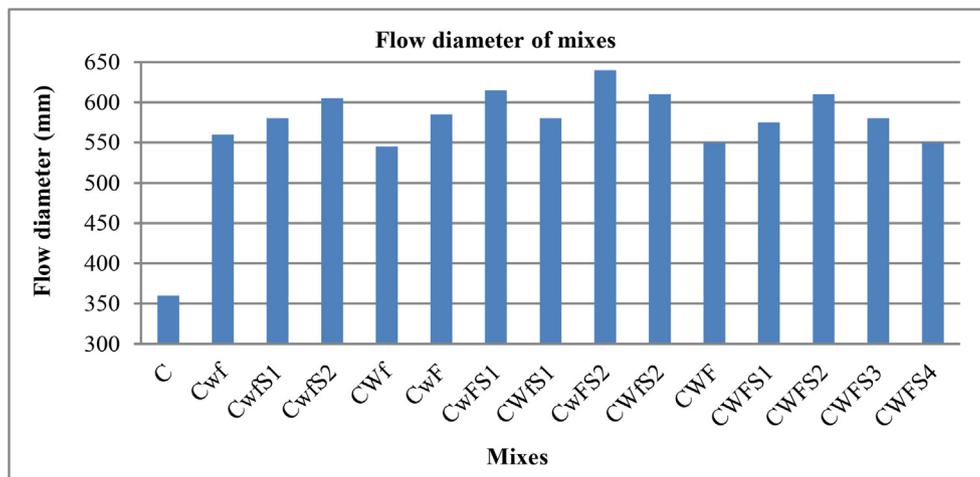


Fig. 4. Flowability of concrete mixes from Abram's cone flow test.

crystalline imparts more friction and inhibits the flow. Thus, the mixes containing null voids with a higher amount of microsilica and flyash should promote more flow than those containing higher amounts of WMF based on shape. Since all these materials are intermixed it is difficult to access the exact dominance of each particle type, which further becomes subtle when the viscous forces also come in action.

An increase in the flowing ability has been observed when the cement in normal concrete is replaced with either WMF & flyash, or with WMF-flyash-microsilica combination (Eqs. (1), (2), (3), (4), and (5)). This is due to the decrease of angular and crystalline cement particles. Though WMF tries to reduce the flow due to its particle shape but flyash or flyash-microsilica presence overcomes this resistance. Hence those mixes which contain more flyash in comparison to WMF exhibit higher flowing ability (Eq. 1). Where microsilica is also present the flow tends to increase on account of microsilica's shape (Eqs. (2), (3), and (4)) but excessive microsilica increases the viscous forces enough due to an increase in surface tension of water on account of water adsorption by extremely fine microsilica particles, and adhesion of microsilica with other particles, thereby reducing the flow (Eq. 5). Hence it has been seen that flow increases up to 5% microsilica content. The flow increases from 380 in mix C to 580, 550, 590 and 550 in mixes Cwf, Cwf, CwF, and CwF respectively. Therefore it is apparent that even though the number of voids gets reduced on substitution of cement with these admixtures which should promote more friction on account of increase in inter-particle contact, but the flow increases because flyash increases the flow due to its shape and negative charge, and microsilica increases flow on the basis of its shape by lubrication effect. WMF also increases the flow in comparison to cement particles because of its needle-shaped particles which get adsorbed over cement particles and reduce cohesion amongst them because of the separation caused by their rough acicular surfaces.

A comparison of flow values caused by microsilica in Eqs. (2) and (3) makes it coherent that microsilica is highly beneficial in reducing the frictional effect of WMF. The flow value jumps from 550 in mix Cwf to 605 in mix Cwfs2, whereas it varied from 580-600 in mix Cwf-Cwfs2 which contains just 5% WMF. The highest flow has been shown by mixes containing 5% WMF and a 10% flyash. Mixes containing 10% each of WMF and flyash give good flow up to 5% microsilica. Results from the V Funnel flow time test also indicate similar relationships.

Also, it is observed from Eq. (1) that the frictional effect of WMF predominates over the ball bearing effect of flyash. Results from the V Funnel flow time test also indicate similar relationships.

3.2. Segregation resistance

Fig. 5 shows the results for various concrete mixes through V funnel test for flow time after 5 min, which indicates their segregation

resistance. EFNARC guidelines suggest this value in range 9–15 seconds for self-compacting concrete. Most of the mixes showed this capability except Cwf which proves that WMF with a low volume of pozzolans can't produce a segregating resistant concrete.

Segregation resistance is inversely proportional to the time taken by the concrete mix to flow through the V funnel after 5 minutes of keeping it calm in the funnel. This does not mean that whatsoever factors that induce flow are also responsible for inducing segregation resistance to the concrete. In fact, viscous forces and inter-particle frictional forces increase segregation resistance as the particles are not allowed to settle under gravity due to these forces. But an excessive increase in these forces decreases the flowing ability of concrete, which is the reason for the fixation of upper limit of flow time at 15 seconds in order to check the segregation resistance of concrete. Microsilica beyond 7.5% increases viscous forces too much, therefore it has been seen in mix CWFS4 (Fig. 5) that flow time has reached 15 seconds. WMF increases inter-particle friction, therefore mix Cwf, having a higher percentage of WMF in comparison to flyash makes the concrete too stiff that it does not flow within 15 seconds. All of this is attributed to the acicular shape of WMF which interlocks aggregates and other particles, and increases the time of flow. But it also ensures that the particles do not segregate. That is why most of the mixes containing even 10% WMF have shown optimal flow which passes the segregation resistance test. Mixes Cwf and CwF prove this point. It is obvious that flyash tends to increase the flow and higher contents of flyash along with WMF or WMF-microsilica give a good value of segregation resistance. Had flyash been used alone, then it might have reduced the segregation resistance. Alike flowing ability, the increment or decrement in segregation resistance also depends upon the cumulative effect of viscous and frictional forces.

Hence a segregation resistant concrete could be produced if viscous forces or frictional forces, or both are optimal such that the concrete does not become too stiff. With the introduction of RCA, the frictional forces increase in the interfacial transition zone which needs to be smoothed over by the ball bearing effect of additional microsilica. Literature provides information that SCC mixes containing WMF require not more than 7.5% microsilica (Sharma et al., 2018), but it could be seen for mix CWFS3 & CWFS4 (where microsilica varies from 7.5% to 10%) that more than 7.5% microsilica can be used to obtain good segregation resistance.

3.3. Passing ability

Fig. 6 shows the results for the height difference of various concrete mixes through J Ring, which indicates their passing ability. EFNARC guidelines state that mixes having a height difference in this test, in range 0–10mm have qualities of passing through obstructions. The results indicate that mixes containing higher volumes of WMF (twice that of

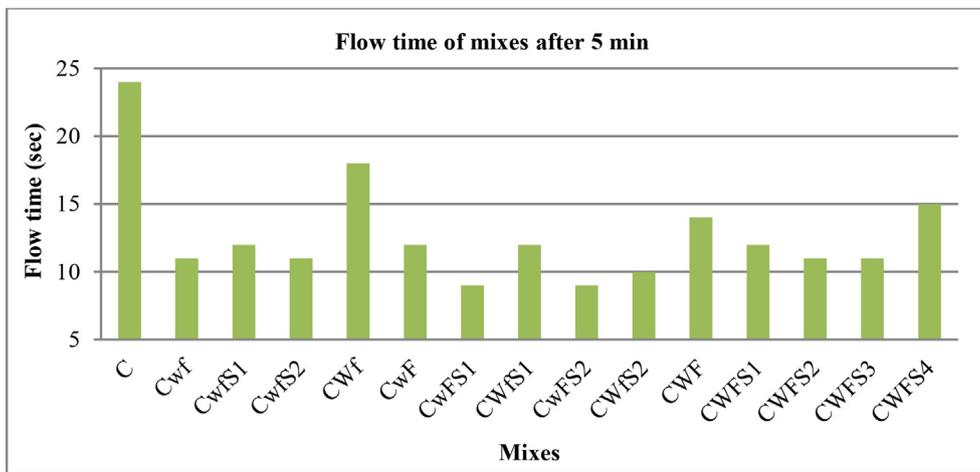


Fig. 5. Segregation resistance of concrete mixes from V funnel test.

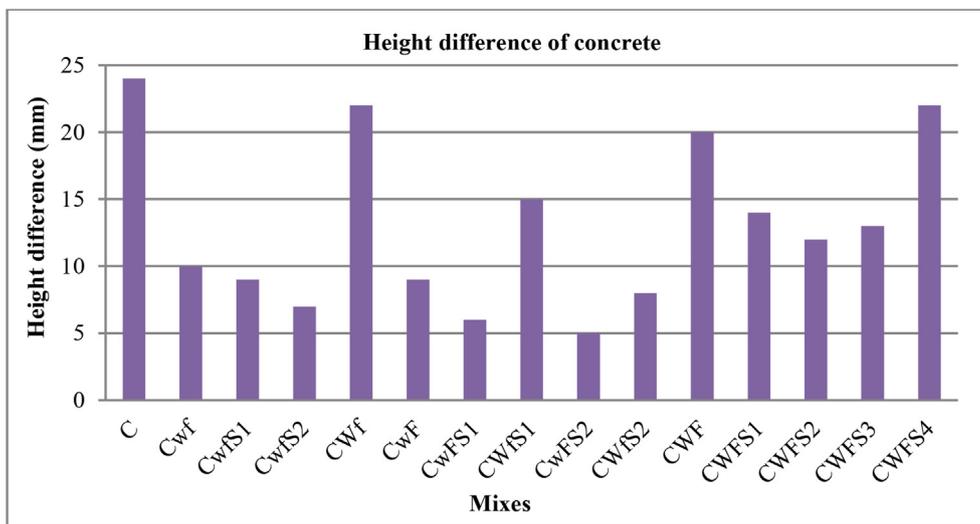


Fig. 6. Passing ability of concrete mixes from J Ring height difference test.

flyash) and microsilica (above 5%) have a lesser passing ability. On average, the results suggest that it is essential to add 5% microsilica when the concrete contains larger amounts of WMF and RCA. Also, it is essential to note that larger volumes of flyash in mixes CWF-CWFS4 is not able to introduce passing ability, which indicates that flyash is only beneficial to impart flow to concrete. A decrease in height difference in these mixes with the introduction of microsilica up to 5% shows that microsilica is effective even in those mixes which contain higher volumes of WMF and flyash. This indicates that the passing ability of mixes depends more on cohesive forces than frictional forces. With the filling of voids through fine admixtures like WMF and flyash the cohesion between cement particles decreases. Interparticle friction between WMF further adds to this reduction. Microsilica though has a negative charge which should reduce the cohesion between cement particles, but its higher adhesive property binds the cement particles as well as RCA with thick pore solution and makes the concrete homogeneous. All particles thus bound in between pore solution flow altogether which improves the passing ability of mixes. Higher content of microsilica increases the viscous forces too much as explained earlier, which reduces the flowing ability, thereby reducing the passing ability of concrete.

3.4. XRD analysis

by X'pert High score application which aims to provide the percentage of different hydrated constituents after 14 days of curing period. The method is based on finding the individual intensities of different hydrated compounds from cumulative peak intensity. All the peaks are evaluated to find the cumulative intensity of a certain hydrated compound expressed as a percentage of the total peak intensities. It will not

Table 1
X-ray diffraction data of pastes.

Mix	Percentage of constituents	% Ettringite	% CH	% CSH	% C ₃ A
C	100C	2.3	9.8	37	5.5
CwF	90C+5W+5F	2.4	8.2	39.3	5.8
CwFS1	87.5C+5F+5W+2.5M	2.5	7.9	41.6	6
CwFS2	85C+5F+5W+5M	3.1	7.6	46.3	6
CwF	85+5F+10W	2.2	8.1	42.2	5.9
CwF	85+10F+5W	2.3	12.7	40.2	5.1
CwFS1	82.5+10F+5W+2.5M	2.4	12.8	41.5	5.5
CwFS1	82.5+5F+10W+2.5M	2.3	7.3	46.7	5.5
CwFS2	80+10F+5W+5M	2.9	8.4	42.6	6
CwFS2	80+5F+10W+5M	3	6.2	48.4	5
CWF	80+10F+10W	1.7	8.5	45.3	6.3
CWFS1	77.5+10F+10W+2.5M	2.1	6.6	47.8	6.4
CWFS2	75+10F+10W+5M	2.5	6.1	48.8	8.6
CWFS3	72.5+10F+10W+7.5M	2.9	6.2	46.9	5.6
CWFS4	70+10F+10W+10M	3.6	6.1	46.4	5.8

Table 1 shows the X-Ray diffraction data of different pastes evaluated

be useful to perform this test at a very early or later stage as in one case the peak data will be too less to study whereas in the other it will be too cumbersome and crowded. If % ettringite, CH, CSH, and C_3A are summed for pure cement, 100% intensity is not obtained as the peaks signify other hydrated and unhydrated compounds too, which are not significant for strength and durability analysis. It was also decided to perform SEM image analysis of concrete mixes after 7 days to record the initial formation of hydrated products in the concrete. At a later stage, the SEM image analysis does not depict the formation trend of hydrated products and all images seem to be similar in a more or less manner. The X-Ray data served as an aid to make a continuous evaluation of the hydration process.

Use of WMF reduces both CH and ettringite, though CH is efficiently reduced (observed in mixes Cwf, CWf, and CwF and CWF with CH content of 8.2%, 8.1%, 12.7% and 8.5% respectively, and ettringite content of 2.4%, 2.2%, 2.3% and 1.7% respectively). Flyash is as effective as WMF in reducing ettringite but it lacks the potential comparatively in the case of CH. Microsilica plays a major role in the reduction of CH but the results coherently indicate that ettringite formation increases with an increase in microsilica content, as have been verified by Sharma et al. (2017). This may be due to the smaller size of microsilica which is not able to do grain size refinement as effectively as WMF or flyash. Ettringite formation is hindered much by bigger size WMF and flyash (Sharma et al., 2018). On the other hand, CH hexagonal particles are easily consumed by secondary hydration done by highly reactive microsilica followed by WMF and flyash. WMF scores over flyash in mitigating CH because of its more effective grain size refinement.

Microsilica is highly effective in increasing CSH production during the initial period. This could be easily verified from XRD analysis of paste specimens after 7 days curing. WMF holds the second place in improving CSH content. This is verified from the CSH rise trend in mixes C-Cwf-CwF-CWF: 37%- 39.3%- 40.2%- 42.2%-45.3%.

3.5. Abrasion resistance

The abrasion resistance of concrete mixes is evaluated in terms of percent weight loss against abrasion under the sandblast. These values and variation of mixes have been shown in Fig. 7.

The percent loss of weight of normal concrete mix is 0.31% after 30 days curing which is quite higher than the weight loss of all the mixes in general. Three mixes Cwf, CwF, and CwFS1 which contain a low content of WMF and microsilica gave a higher value of percent weight loss. This proves that WMF and microsilica result in a high value of abrasion resistance whereas flyash reduces it. Fig. 8 shows the SEM images of Cwf and CwFS1 wherein lots of voids and unreacted bigger round particles of flyash could be seen.

Since all of these materials are fine in nature it was expected that these would reduce the pore volume, thereby resulting in a smooth concrete mix which should have lesser abrasion resistance. Also, WMF was expected to increase the friction of dry concrete because of its fibrous acicular nature (Singh and Madan, 1994), which creates confusion as to how it will behave, whether as pore filler or a fiber. Looking at the results of mixes containing higher contents of WMF and flyash respectively, it is quite coherent that apart from texture there is another parameter affecting the abrasion resistance. While comparing these results with the compressive strength results it was found that mixes containing higher strength have lesser weight loss even if their pore volume/texture is overlooked, especially mixes containing WMF. There is an increase in the compressive strength as well as abrasion resistance with an increment of WMF content in the mix. This may be due to the reinforcing and interlocking effect of WMF in between the mortar, and between mortar and aggregate interface in the dry state of concrete (Banthia et al., 1995; Bayasi and Zeng, 1993; Cunha et al., 2010; Felt, 1960; Fwa and Paramasivam, 1990). Fig. 9 shows the SEM image of mix CWF and CwF. A high density of overlapping CSH seeming to be hydrated on cross-linking WMF particles in the image of CWF proves this point. CwF, on the other hand, has a large amount of CH and a small amount of CSH.

With an increase in microsilica content above 7.5%, a reduction in abrasion resistance has been observed in mix CWFs4. This may be due to a high rate of self desiccation due to the presence of a large volume of very fine material between cement voids. The water competition between particles forces either of microsilica or WMF, or flyash to remain unreacted and increase the weight loss on abrasion. Even though it reduces the pore volume but the mortar remains weaker. One more observation supports this fact in this way; if weight loss of weaker mortar starts once under abrasion, then even if a strong mortar phase exists in between, still the abrasion loss continues as the latter is sandwiched between weak cohesive layers.

3.6. Compressive strength

In the initial stages when the concrete is wet, the fine material like microsilica, WMF and flyash travel through the pore solution to the voids in between cement particles. This process also liberates water and fills the voids with a solid material which is further subjected to secondary hydration in coming ages thus making dense CSH formation with the least amount of entrapped and capillary voids. Though the rate of secondary hydration may vary based on the physical and chemical properties of the admixture, the filler effect tends to increase the compressive strength of concrete. It is beneficial to use an admixture if the cumulative improvement done by filling of voids and secondary hydration exceed the strength gain imparted by pure cement binder at all ages of curing (Bentz

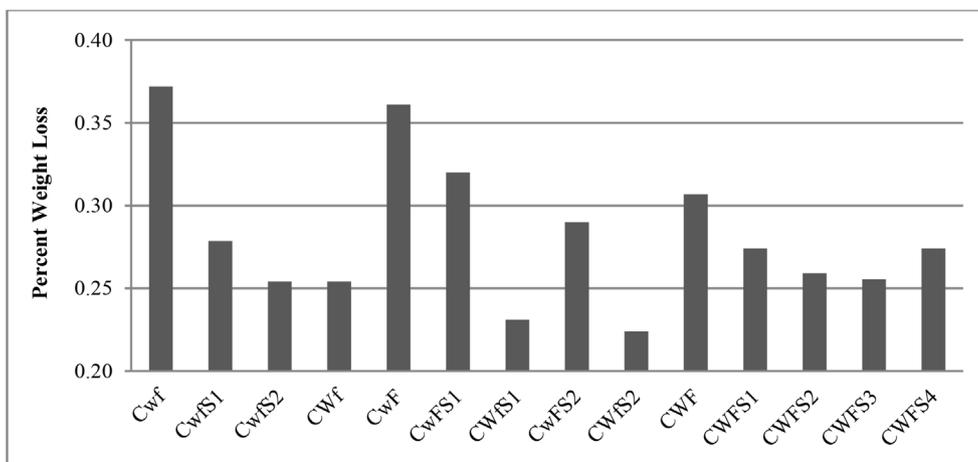


Fig. 7. Percent weight loss of various concrete mixes under abrasion.

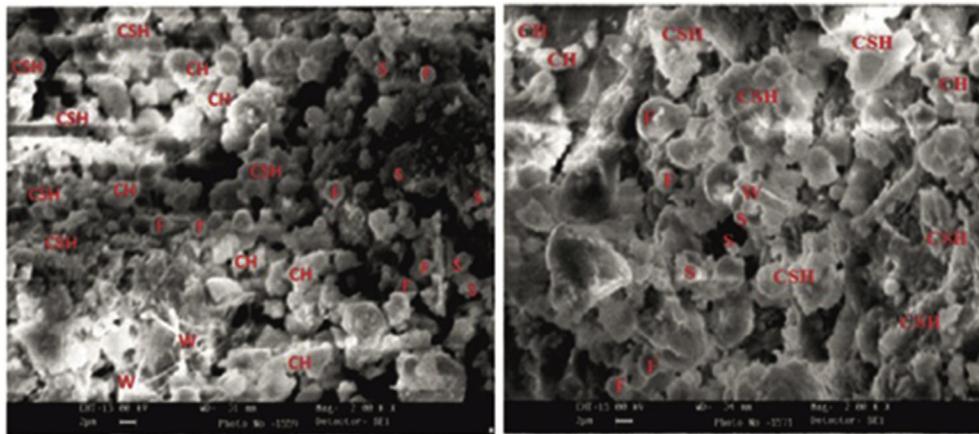


Fig. 8. SEM images of Cwf (left) and CwfS1 (right).

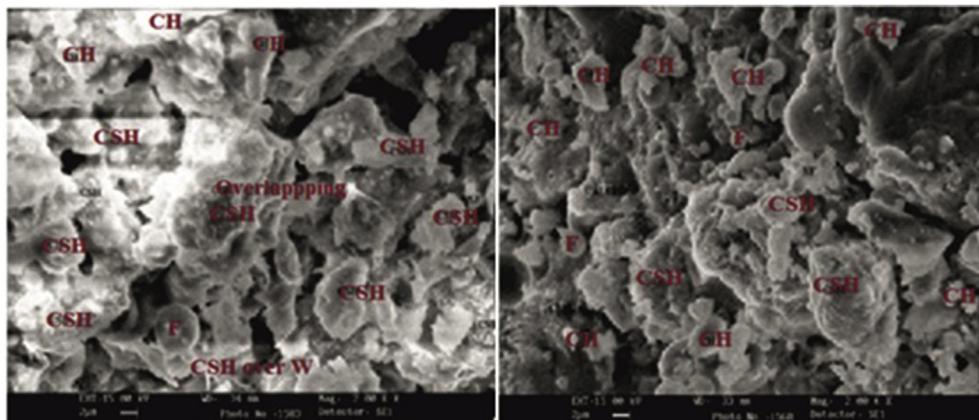


Fig. 9. SEM image of CWF (left) & CwF (right).

et al., 2008). Apart from this WMF has a reinforcing effect also which complements the pozzolanic effect of WMF. Though WMF is also a weak pozzolan but the combined effect of reinforcement and secondary hydration makes it an effective strength enhancer at initial stages. Flyash, on the other hand, is a weak pozzolan whose rate of reaction is slow when surplus pore water is present, and it becomes active at later stages (30–90 days). All these factors influence the strength of mortar and concrete to a

big or small extent depending upon the physiology of these matrices. Figs. 10 and 11 show the compressive strength of mortar and concrete mixes respectively.

Mortars do not have interface whereas concretes have an interface between mortars and aggregates. In the case of mortars, during initial curing periods, the strength gain for flyash is lesser than WMF, because the reinforcing effect of WMF binds the mortar quickly. More is the

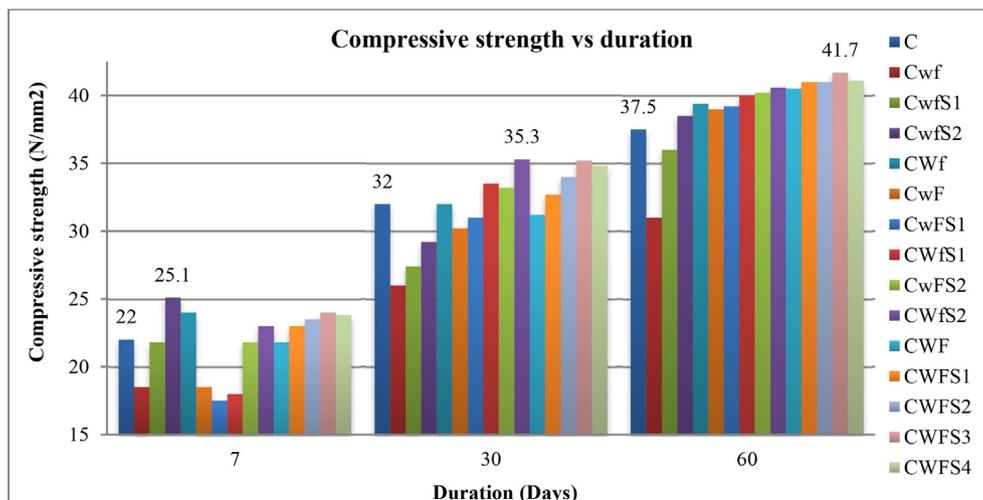


Fig. 10. Compressive strength of mortar mixes after different durations.

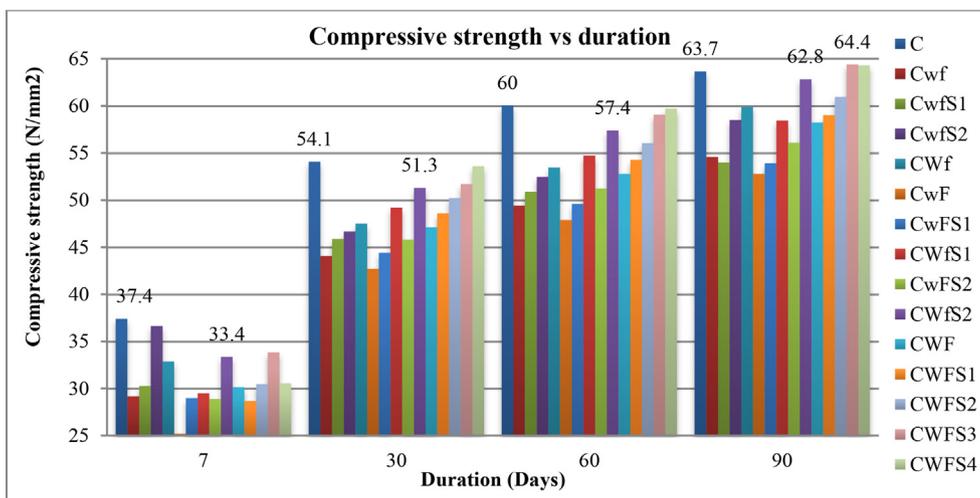


Fig. 11. Compressive strength of concrete mixes after different durations.

hydration more will be the reinforcement. Hence, during the initial period, the mortar mixes containing higher WMF content show higher strength than others. After 30 days of curing no more improvement due to reinforcement could be possible as interlocking has already been done. Further strength improvement occurs due to the pozzolanic effect only. Since flyash is a stronger pozzolan than WMF under a lesser pore water volume, therefore it enhances strength to a greater extent. Therefore at 60 days, the strength of all the mixes seems to be equal. Microsilica complements these mixes equally.

In the case of concretes, the reinforcing effect of WMF enhances the strength of the interfacial transition zone (the zone between aggregates and mortar) a lot. Even because of its acicular nature it forces the hexagonal grains of calcium hydroxide and big needle-shaped ettringite to orient into a denser mass which is called as grain size refinement. This fact is verified from XRD analysis wherein it has been found that WMF controls the formation of ettringite and CH. Also, SEM images of mix Cwf (Fig. 8), CWF (Fig. 9) and CWf (Fig. 12) prove that CWf and CWF have lesser CH and ettringite. The SEM image of mix CWf in Fig. 12 shows a negligible amount of ettringite, least amount of CH and a high amount of overlapping dense CSH.

Hence WMF has an extra advantage in the case of concrete which is observed from higher strengths of mixes Cwf, CwfS1 and CwfS2 in Fig. 11. Strength testing was carried up to 90 days to check if mixes containing higher amounts of flyash could reduce the strength gap after 60 days, but the results prove that WMF pozzolanic effect does not allow this gap to diminish. Microsilica highly improves the interfacial transition zone because of being finer and stickier, and more reactive than other admixtures. It easily penetrates the transition zone, does the hydration and sticks to the aggregates thereby increasing the strength of the interface. The improvement done is so effective that it continues to exist afterwards.

Overall, the mixes containing higher amounts of both WMF (10%) and microsilica ($\geq 5\%$) yield high compressive strength at all stages of curing in mortars irrespective of the flyash content. In the case of concrete mixes, only CWFS3 and CWFS4 prove to be better than normal mixes after longer curing periods which necessitates that higher contents of microsilica ($> 7.5\%$) are required to develop sufficient strength in the interface. Higher content of CSH at seven days from XRD analysis for mixes CWFS3 (46.8) and CWFS4 (46.4) prove this fact. SEM images of these mixes are shown in Fig. 13, which also show a very dense matrix containing a high amount of overlapping CSH and a negligible amount of CH and ettringite.

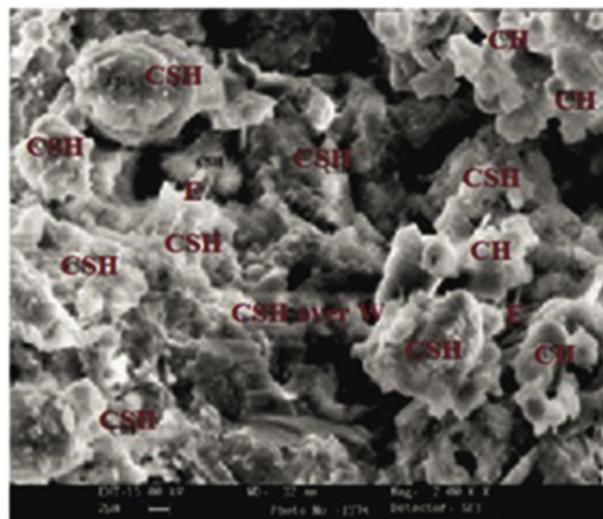


Fig. 12. SEM image of mix CWf.

3.7. Flexural strength

Figs. 14 and 15 show the flexural strength of mortar and concrete mixes respectively.

Since the compressive strength variation of mortars remained constant at all durations, therefore only 30 days flexural strength of mortars has been studied to save time and funds. Understanding flexural strength variation of mortars is simple as all the mixes showed higher flexural strength (than normal mortar) with the inclusion of WMF, flyash, and microsilica in a uniform manner. Microsilica improved strength to a larger scale than WMF or flyash. Rather, it is impossible to say from the results whether WMF is effective or flyash. Both WMF and flyash improved strength quite equally. This implies clearly that pozzolanic property has a significant effect in comparison to reinforcing behavior in the case of mortars. Mix CWFS3 gave higher strength than mix CWFS4 which indicates weakening of mortar due to self-desiccation, when microsilica content increases beyond 7.5%.

For concrete, it was found that none of the mixes yielded flexural strength even close to that of a normal mix, but CwfS2 and CWFS3 at 90 days. XRD analysis of mix CWFS2 after seven days curing shows 48.8 percent of CSH produced, 6.1% of CH and 2.5% of ettringite. These parameters are best for a given mix and prove the point stated above. The SEM image of this mix has been shown in Fig. 16 which also points out

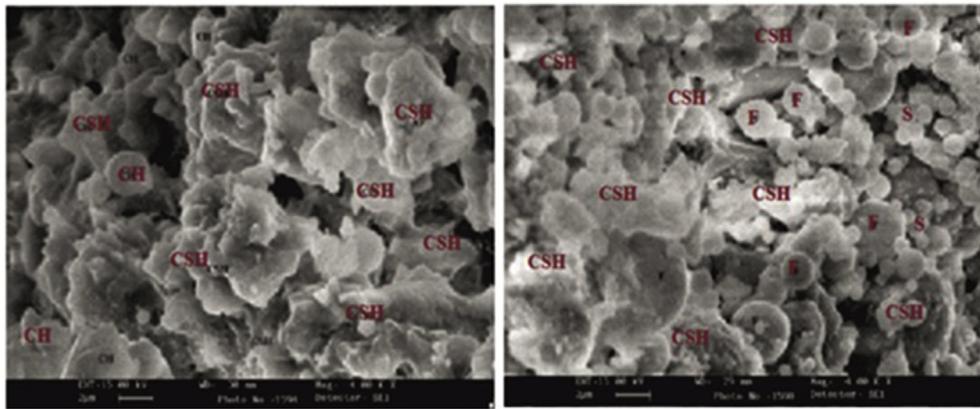


Fig. 13. SEM images of mix CWFS3 (left) and CWFS4 (right).

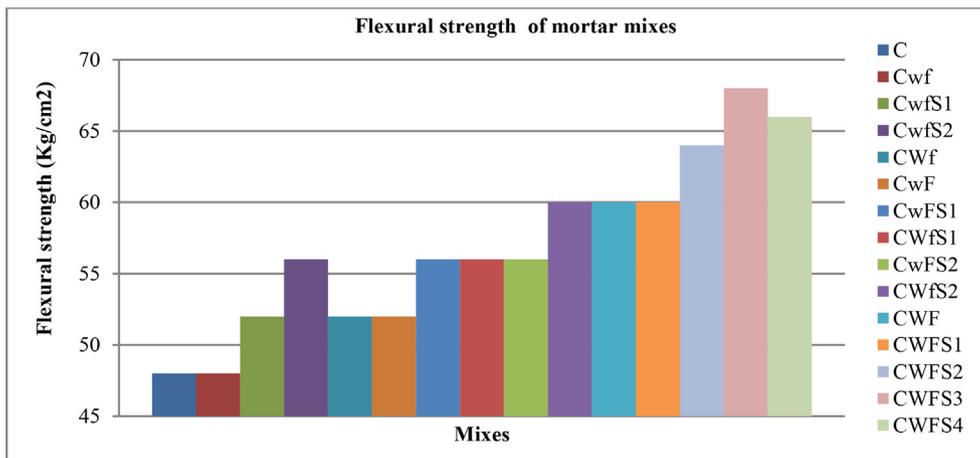


Fig. 14. Flexural strength of mortar mixes after 30 days.

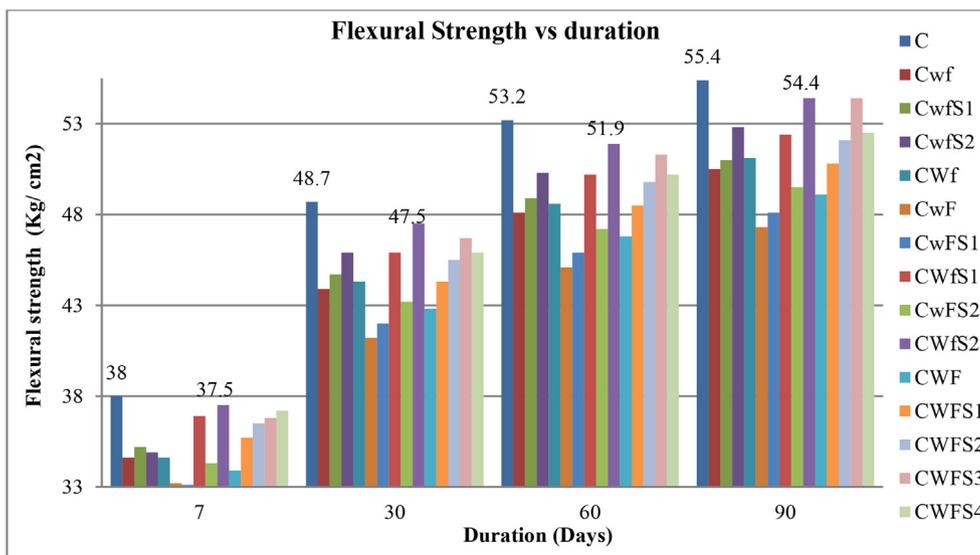


Fig. 15. Flexural strength of concrete mixes after different durations.

large and dense CSH formations.

Specifically, the mixes containing flyash and WMF in proportions 1:1 to 1:2, along with higher proportions of microsilica yielded higher strength. XRD analysis shows that mixes CwfS2, CWfS2, CWFS2 have higher CSH formations at 46.3, 48.4 and 48.8% respectively, which are

higher than other mixes. SEM images of mixes CwfS2 and CWfS2 are shown in Fig. 17, which shows densely packed CSH over light grey aggregate surfaces.

As the flexural tensile strength depends more upon the cohesive forces between the binding particles in mortar-mortar and mortar-

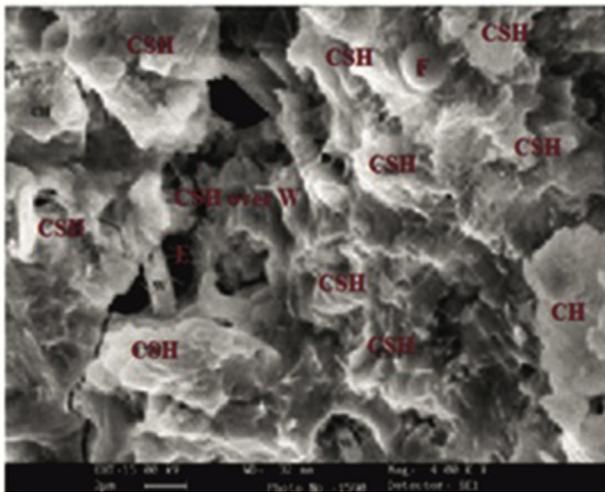


Fig. 16. SEM image of mix CWFS2.

aggregate phase, and lesser on the density of concrete, therefore the pozzolanic action of flyash is not sufficient enough in this case. WMF has both pozzolanic and reinforcing action and microsilica has the strongest pozzolanic action. Both these admixtures improve the strength of mortar as well as interface more effectively than flyash.

It has been found from the literature that two ITZs exist between new mortar and old aggregates (recycled aggregates) (Abed et al., 2018). The ITZ circling old aggregate (40–50 microns) closely has a rough texture, over which old mortar exists which is quite denser than the old ITZ. The new ITZ (50–65 microns) circling old mortar is highly porous because of a high amount of water adsorption by old mortar at its surface (Kumar and Kaushik, 2004; Larbi, 1993; Santos et al., 2019). Also, the heterogeneity existing between old and new mortar on account of the difference between their stiffness encourages the new mortar to leave the space for water in between them (Vargas et al., 2017). This new ITZ could be made dense by the combined efforts of microfibers and silica fume and not by flyash as shown in Fig. 18. Microfibers also make cross-links thereby reinforcing old mortar with the new ITZ, and further the new ITZ with new mortar (proved from SEM images showing overlapping CSH hydrated over WMF particles). Flyash just compliments this process by reducing the porosity of new ITZ in between as it does not have the ability to get adsorbed over the old mortar because of its lower surface area and bigger size than microsilica.

Hence the flexural strength of those recycled aggregate concrete mixes which contain at least 10% WMF and 7.5% microsilica can approach that of a normal concrete mix.

4. Conclusion

The study did not put an elaborate finding on using various contents of RCA as the focus of the study was to replace coarse aggregates fully with RCA, and to find out the possible combinations of pozzolanic material, cement, and WMF which could yield a good strength and abrasion-

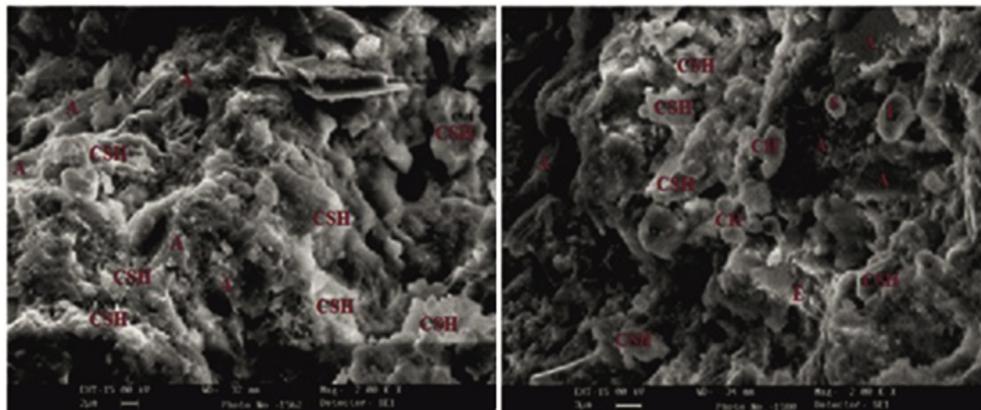


Fig. 17. SEM images of mix CWFS2 (left) and CwfS2 (right).

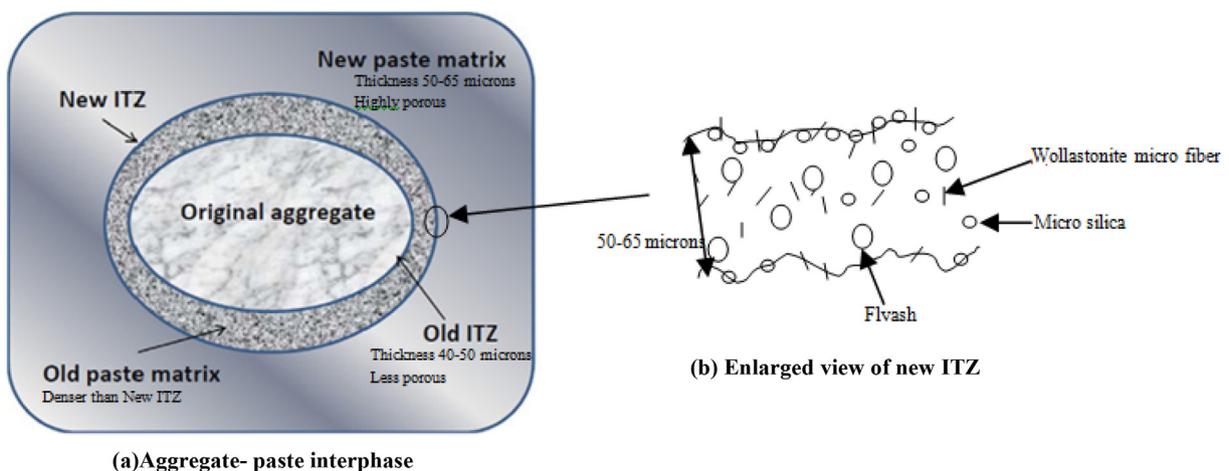


Fig. 18. Role of microfibers, fine & normal size pozzolans in aggregate-paste interphase (left) and enlarged view of new ITZ (right).

resistant SCC. From this study following conclusions could be made:

- As far as strength is concerned (compressive or flexural), it is beneficial to use WMF in larger amounts ($\geq 10\%$), almost double than flyash.
- Use of microsilica above 7.5% along with high volumes of WMF (or a microsiber) could be used to improve the bond at the interface which may bring the strength of concretes containing RCA equal to that of normal concrete made of normal aggregates.
- Strength of mortar as well as the texture of concrete, both affect the abrasion resistance of concrete. Strength of mortar could be improved with the use of microfibers (WMF in the present case) but it makes the texture rough. The texture could be improved by pore size and grain size refinement imparted by pozzolans whose quantity should depend upon the quantity of fiber (like in this case pozzolans: WMF ratio is 1:2).
- Recycled aggregates have lesser strength than normal aggregates, but it's not their strength which largely reduces the strength of the resulting mix. Rather it's the bond between them and the mortar at the interface. This is apparent from the low strength of mixes containing either no microsilica or 2.5% microsilica, as microsilica has been found to improve the interface.
- It is recommended to prioritize the content of pozzolans (for flow) at first instance while trying to yield a SCC with RCA. Microsilica should be used preferably above 7.5% to improve the ITZ for such concretes. Based on the content of medium-sized pozzolan (like flyash), micro-fiber's quantity should be used to bring desired characteristics in the concrete.
- Pozzolans can't introduce enough resistance against shear stresses and microfibers can't make the concrete homogeneous, and thus smooth. The use of microfiber is a must even if somehow the pozzolans can improve the strength of mortar against compression and abrasion, since only microsilica and microfibers altogether could improve the ITZ. This statement could not be passed for all types of microfibers with surety because WMF has played the role of a fiber as well as a pozzolan (better able to develop a bridge between mortar and ITZ).
- Literature study suggests that 5% of microsilica is enough to improve the strength of concrete containing 20% flyash and normal aggregates. Comparison with this study indicates that recycled aggregates and the use of microfibers demand extra microsilica.

Declarations

Author contribution statement

Shashi Kant Sharma: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Abed, M., Nemes, R., Tayeh, B.A., 2018. Properties of self-compacting high-strength concrete containing multiple use of recycled aggregate. *J. King Saud Univ - Eng. Sci.* ACI Committee 232-94, 1994. Use of Flyash in Concrete. ACI Publication, Farmington Hills, USA.
- Assaad, J.J., 2017. Influence of recycled aggregates on dynamic/static stability of self-consolidating concrete. *J. Sustain. Cement-Based Mater.* 6, 345–365.
- Assaad, J.J., Daou, Y., 2017. Behavior of Structural Polymer-Modified concrete Containing Recycled Aggregates, pp. 874–896.
- Banthia, N., Yan, N., Chan, C., Yan, C., Bentur, A., 1995. Bond slip mechanisms in steel micro-fiber reinforced cement composites. *J. Comp., Mater. Res. Soc.* 370, 529–537.
- Bayasi, Z., Zeng, J., 1993. Properties of polypropylene fibre reinforced concrete. *ACI Mater. J.* 90 (6), 605–610.
- Bentz, D.P., Stutzman, P.E., Garboczi, E.J., 1992. Experimental and simulation studies of the interfacial zone in concrete. *Cement Concr. Res.* 22 (5), 891–902.
- Bentz, D.P., Sant, G., Weiss, J., 2008. Early-age properties of cement-based materials part I: influence of cement fineness. *J. Mater. Civ. Eng.* 20 (7), 502–508.
- Cohen, M.D., Goldman, A., Chen, W.F., 1994. The role of Silica gel in mortar: transition zone versus bulk paste modification. *Cement Concr. Res.* 24 (1), 95–98.
- Cunha, V.M.C.F., Barros, J.A.O., Sena-Cruz, J.M., 2010. Pullout behavior of steel fibers in self-compacting concrete. *J. Mater. Civ. Eng.* 22 (1), 1–9.
- Dey, V., Kachala, R., Bonakdar, A., Mobasher, B., 2015. Mechanical properties of micro and sub micron wollastonite fibers in cementitious composites. *Constr. Build. Mater.* 82, 351–359.
- EFNARC, 2002. Specification and Guidelines for Self-Compacting Concrete. Association House, 99 West Street, Farnham, Surrey, GU9 7EN, UK.
- EFNARC, 2005. The European Guidelines for Self-Compacting Concrete: Specification, Production and Use. Association House, 99 West Street, Farnham, Surrey, GU9 7EN, UK.
- Faleschini, F., Marzi, P.D., Pellegrino, C., 2014. Recycled concrete containing EAF slag: environmental assessment through LCA. *Eur. J. Environ. Civil Eng.* 18 (9), 1009–1024.
- Felt, E.J., 1960. Repair of concrete pavement. *J. Am. Concr. Inst. Proc.* 57, 139–153.
- Fwa, T.F., Paramasivam, P., 1990. Thin steel fibre cement mortar overlay for concrete pavement. *Cement Concr. Compos.* 12, 175–184.
- Ghugal, Y.M., 2003. Effects of steel fibers on various strengths of concrete. *ICI J.J. Indian Roads Congr.* 4 (3), 23–29.
- Grunewald, S., Walraven, J.C., 2001. Rheological study on the workability of fiber reinforced mortar. In: *Proceedings of the Second International Symposium on Self Compacting Concrete*, Tokyo, Japan, pp. 127–136.
- Gupta, S., Kantaroo, V.V.L., Sengupta, J.B., 2008. Evaluation of polyester fiber reinforced concrete for use in cement concrete pavement works. *Road Mater. Pavement Des.* 9 (3).
- Hossain, K.M.A., Lachemi, M., Sasmour, M., Sonebi, M., 2012. Influence of polyvinyl alcohol, steel and hybrid fibers on fresh and rheological properties of self-consolidating concrete. *J. Mater. Civ. Eng.* 24 (9), 1211–1220.
- Kalla, P., Misra, A., Sancheti, G., 2011. "Properties of wollastonite and flyash aided concrete", *Indian highways. J. Indian Roads Congr.* 39 (12), 25–31.
- Kaushik, S.K., Gupta, V.K., Gupta, S., 1994. Properties of fresh and hardened SFRC. In: *Proceedings of the National Seminar on Fiber Reinforced Cementitious Products*, Roorkee, India, January, pp. 247–257.
- Khayat, H.K., Aitcin, P.C., 1992. Silica fume in concrete- an overview. In: *Malhotra, V.M. (Ed.), Flyash, Silica Fume, Slag and Natural Pozzolans in Concrete*, pp. 835–872. ACI SP-132, Detroit, Michigan, 2.
- Krishnamoorthy, T.S., Kumar, B.H., 1994. Influence of steel fibers on the compression and flexural behavior of concrete. In: *Proceedings of the National Seminar on Fiber Reinforced Cementitious Products*, Roorkee, India, pp. 25–32.
- Kumar, P., Kaushik, S.K., 2004. Transition zone in self compacting concrete. *Indian Concr. J.* 78 (6), 39–43.
- Larbi, L.A., 1993. Microstructure of the interfacial zone around aggregate particles in concrete. *Heron J.* 38 (1), 5–69.
- Lawler, J.S., Zampini, D., Shah, S.P., 2005. Microfiber and macrofiber hybrid fiber-reinforced concrete. *J. Mater. Civ. Eng.* 17 (5), 595–604.
- Lei, Dong-Yi, Guo, Li-Ping, Sun, Wei, Liu, Jiaping, 2016. A new dispersing method on silica fume and its influence on the performance of cement-based materials. *Constr. Build. Mater.* 115, 716–726.
- Low, N.M.P., Beaudoin, J.J., 1992. Mechanical properties of high performance cement binders reinforced with Wollastonite micro-fibres. *Cement Concr. Res.* 22 (5), 981–989.
- Martinie, L., Rossi, P., Roussel, N., 2010. Rheology of fiber reinforced cementitious materials: classification and prediction. *Cement Concr. Res.* 40, 226–234.
- Matar, P., Assaad, J.J., 2017. Concurrent effects of recycled aggregates and polypropylene fibers on workability and key strength properties of self-consolidating concrete. *Constr. Build. Mater.* 199, 492–500.
- Mehdipour, Iman, Ali Libre, Nicolas, Shekarchi, Mohammad, Khanjani, Maryam, 2013. Effect of workability characteristics on the hardened performance of FRSCCMs. *Constr. Build. Mater.* 40, 611–621.
- Mehta, P.K., 1985. Influence of Flyash characteristics on the strength of Portland-Flyash mixtures. *Cement Concr. Res.* 15 (4), 669–674.
- Pierre, P., Pleau, R., Pigeon, M., 1999. Mechanical properties of steel microfiber reinforced cement pastes and mortars. *J. Mater. Civ. Eng.* 11 (4), 317–324.

- Ransinchung, G.D., Kumar, B., 2010. Investigations on pastes and mortars of ordinary portland cement admixed with Wollastonite and Microsilica. *J. Mater. Civ. Eng.* 22 (4), 305–313.
- Ransinchung, G.D., Kumar, B., Kumar, V., 2009. Assessment of water absorption and chloride ion penetration of pavement quality concrete admixed with Wollastonite and Microsilica. *Int. J. Constr. Build. Mater.* 23 (2), 1168–1177. Elsevier.
- Santos, S., Da Silva, P.R., Brito, J.de, 2019. "Self-compacting concrete with recycled aggregates – a literature review". *J. Build. Eng.* 22, 349–371.
- Sharma, S.K., Ransinchung, G.D., Kumar, P., Roy, A.K., 2017. Comparison of permeability and drying shrinkage of self-compacting concrete admixed with Wollastonite micro fiber and flyash. *Int. J. Eng. Trans. B: Appl.* 30 (11), 1681–1690.
- Sharma, S.K., Ransinchung, G.D., Kumar, P., 2018. Investigating the use of Wollastonite micro fiber in yielding SCC. *Adv. Concr. Constr.* 6 (2), 123–143.
- Singh, G., Madan, S.K., 1994. Shear resistance of steel fiber reinforced concrete. In: *Proceedings of the National Seminar on Fiber Reinforced Cementitious Products*, Roorkee, India, pp. 15–23.
- Soliman, A.M., Nehdi, M.L., 2012. Effect of natural Wollastonite microfibers on early-age behavior of UHPC. *J. Mater. Civ. Eng.* 24 (7), 816–824.
- Taboada, I.G., Fonteboa, B.G., Abella, F.M., López, D.C., 2016. Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis. *Mater. Construcción* 66 (323).
- Tang, W.C., Ryan, P.C., Cui, H.Z., Liao, W., 2016. Properties of self-compacting concrete with recycled coarse aggregate. *Adv. Mater. Sci. Eng.* 3, 1–11.
- Thomas, C., Setién, J., Polanco, J.A., Brito, J.de, Fiol, F., 2019. Micro- and macro-porosity of dry and saturated state recycled aggregate concrete. *J. Clean. Prod.* 211, 932–940.
- Vargas, P., Restrepo-Baena, O., Tobón, J.I., 2017. Microstructural analysis of interfacial transition zone (ITZ) and its impact on the compressive strength of lightweight concretes. *Constr. Build. Mater.* 137, 381–389.
- Zhan, B., Poon, C.S., Shi, C., 2013. CO₂ curing for improving the properties of concrete blocks containing recycled aggregates. *Cement Concr. Compos.* 42, 1–8.