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Comparison of Permeability and Drying Shrinkage of Self Compacting Concrete Admixed with Wollastonite Micro Fiber and Fly Ash

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ABSTRACT

Cement substitution in self-compacting concrete (SCC) is emphasized to conserve environment, reduce cost and utilize waste materials. This paper focuses on comparing the permeability and drying shrinkage of SCC containing Wollastonite micro fiber (WMF), a cheap pozzolanic fiber with respect to fly ash. Microsilica was added for providing required viscosity to maintain homogeneity of the mixes. Trials to check flowability, passability and segregation resistance were conducted on binary, ternary and combined mixes of binder material. Results showed that drying shrinkage reduced by 49% for WMF reinforced concrete, whereas it increased by 1.25% for fly ash ones as compared to normal concrete. Permeability coefficient decreased by 82 and 74%, respectively. Capillary voids influenced the permeability of hardened concrete, but drying shrinkage was largely influenced by the rate of gain of tensile strength and expanding ettringite. Notably, fly ash is not a reliable admixture for controlling drying shrinkage of high flow concretes.

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NOMENCLATURE

SFSCC	Semi flowable self compacting concrete	SEM	Scanning electron microscopy
WMF	Wollastonite micro fiber	PQC	Pavement Quality Concrete
OPC	Ordinary Portland cement	MSA	Maximum Size of Aggregate
PCE	Poly Carboxylate Ester	XRD	X Ray Diffraction
MPa	Mega Pascal	CSH	Calcium Silicate Hydrate
FA	Fine Aggregate	CH	Calcium Hydroxide (Slaked Lime)
CA	Coarse Aggregate	C_3A	Tri Calcium Aluminate
BET	Brunauer–Emmett–Teller		

1. INTRODUCTION

Concrete has always manifested two drawbacks; one is brittleness and other drying shrinkage. Fibers have been found to yield quasi-ductile concrete but, workability is affected in this case. Also, there is an ambiguity that whether a permeable concrete has lesser drying shrinkage or not, as both are related to the water present in the concrete matrix. Studies conducted in the past have provided separate results on these properties by comparing them with strength. It was concluded that strength does not bear exact correlation with either permeability or drying shrinkage. Since both permeability and drying shrinkage resistance are dependent on capillary voids, therefore these two properties could be compared with each other to check if one or the other is controlled by other factors to small or large extent.

Verbeck [1] in his study on the pore structure of the hydrated cement paste clearly mentioned the effect of loss of humidity from the paste. It was stated that hydrated paste bears hydrophobic nature due to the presence of pores in it. Two types of pores namely:

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capillary pores/voids and gel pores exist in the hydrated paste. The loss of humidity up to 45 % causes loss of capillary water whereas water in the gel pores remain adsorbed on the paste even at very low humidity. Hence it could be deducted from this study that the admixtures which could reduce the capillary voids into gel pores or could block them from losing the water may efficiently reduce the shrinkage of concrete. It would be obvious that finer admixtures would perform this function quite suitably, but a doubt still exists about the use of these types of fine admixtures. The doubt is based on the shrinkage increment capability of the admixtures on basis of loss of water which was earlier adsorbed on their surfaces. Hence there are more parameters involved. Including either fly ash or ground granulated blast furnace slag in the mix increases shrinkage. Specifically, at a constant water/cement ratio, a higher proportion of fly ash or slag in the blended cement leads to higher shrinkage by some 20 percent with the former material, and by up to 60 percent by later. Sellevold [2] found, that microsilica increases the long term shrinkage. Lomboy et al. [3] investigated the differences in the strength and shrinkage properties of semi flowable self-compacting concrete (SFSCC) and ordinary pavement concrete containing 20% Class F fly ash. Compressive strength, splitting tensile strength, modulus of elasticity and fracture strength of both the concretes were evaluated at 1,3,7,14 and 28 days and were found to have negligible differences except modulus of elasticity, which reduced for SFSCC. Also shrinkage induced cracking was found higher in SCC. Maghsoudi and Dahooei [4] also stated that the use of fine admixtures like microsilica and nanosilica improve the self compacting conditions but they don't make much appreciable difference in hardened properties. Altoubat et al. [5] introduced fly ash in SCC to study restrained shrinkage behavior. It was found that 35% of fly ash highly controlled the shrinkage whereas 50% cement substitution with fly ash could be achieved with respect to control concrete. Hence, it would not be wrong to doubt that fine admixtures could try to promote more shrinkage. Therefore fiber addition is sought in SCC mixes.

Addition of fibers increases bond strength between concrete and reinforcement and reduce the voids in concrete [6]. This was proved by Hashemi and MirzaeiMoghadam [7] also. Polypropylene fibers and nanosilica were utilised in that study to obtain a lightweight void less concrete. Soleimanzadeh and Othuman Mydin [8] stated that flexural strength of a lightweight foamed concrete could be improved by use of either or both fly ash and polypropylene fibers. Wittman [9] clearly distinguishes between two types of shrinkage; plastic and drying. Plastic shrinkage occurs when water is lost from the surface of the hydrated paste in the plastic state of mix, whereas drying shrinkage occurs in the semi hard consistency of the mix. Therefore the shrinkage depends upon the plasticity of the paste too.

Fine admixtures like microsilica, increase the surface area of the paste/mix, and thus cause higher plastic shrinkage, whereas the same admixtures in the semi hard consistency decrease the drying shrinkage of the paste due to reduction of capillary voids and thus induce high rate of strength increment. Lesser fine admixture like fly ash has exactly opposite behaviour. It increase the drying shrinkage whereas decrease the plastic one. Super plasticizers have been found to increase shrinkage by some 10 to 20 percent. However, the changes in the observed shrinkage are too small to be accepted as reliable and generally valid.

Present study aims to yield a high flow self-compacting concrete with wollastonite micro fiber (WMF) at higher volumes, to find out if using this fiber is advantageous over fly ash in terms of permeability and drying shrinkage resistance. Further coherence will be developed regarding which factors make difference between these two properties, if there is any. Hence, yielding of a quasi-ductile shrinkage mitigated fiber reinforced SCC has been attempted here.

2. MATERIALS AND TESTING TECHNIQUES

2. 1. Materials

Ordinary Portland cement (OPC) 43 grade conforming to Indian standard code IS 8112–1995 was used. Graded river sand conforming to Zone–II having fineness modulus of 3.23 and specific gravity of 2.58 was used as fine aggregate. Crushed graded coarse aggregates of 20 mm and 10 mm conforming to IS 383-1970 were used in the proportion of 60:40. The specific gravity of 20 mm and 10 mm aggregates were 2.62 and 2.58, respectively. Fine amorphous wollastonite powder with specific surface and specific gravity values of 827m^2/kg and 2.9, respectively was supplied by Rajwara Stonex Limited was used. Densified 920D grade microsilica had a specific surface and specific gravity values of 18000 m^2/kg and 2.05, respectively. Medium lime Class F fly ash obtained from NTPC Ghaziabad was found to have specific surface and specific gravity values of 350 m^2/kg and 2.52. High water reducing poly carboxylate ether (PCE) based superplasticizer was used to introduce self-compacting workability conditions to the concrete.

2. 2. Paste and Concrete Mixes

Six mixes were constituted by substituting cement with WMF and fly ash, each varying at 10, 20 and 30%. Keeping same substitution levels of WMF and fly ash in cement, twenty four mixes were constituted by further substituting cement with microsilica at 2.5, 5, 7.5% and 10%. Then combined mixes were constituted having cement, fly ash, wollastonite as well as microsilica in such a way that either of wollastonite or fly ash content was varied from 0-10%. Microsilica was introduced between 0-10% in such a fashion that its quantity did not cross either that of wollastonite or fly ash in a given mix (shown in Table 1). After constituting the mixes, a normal concrete mix of 4.5 MPa was designed in accordance with the specifications laid down in IRC 44-2008, details provided in Table 2. Subsequent SCC mixes have been prepared (Figure 1) by sequentially performing the following steps: substituting the binder material, addition of superplasticizer and changing the coarse aggregate to fine aggregate content of the normal concrete mix.

TABLE 1. Mix composition and X ray diffraction data of pastes

Mix	Percentage of constituting material	% Ett	% CH	% CSH	% C_3A
C	100C	2.3	9.8	37	5.5
CF1	90C+10F	2.8	8.9	38.7	5.8
CF2	80C+20F	2.7	6.4	40.2	6.5
CF3	70C+30F	3.2	2.8	42.4	6.7
CFS1	87.5C+10F+2.5M	2.5	10	39.4	5.8
CFS2	85C+10F+5M	2.9	10	40.1	5.8
CFS3	82.5C+10F+7.5M	3.6	7.7	41.3	6.2
CFS4	80C+10F+10M	4.1	4.6	45.9	6.2
CFS5	77.5C+20F+2.5M	2.8	7.2	41.4	5.9
CFS6	75C+20F+5M	2.9	8.6	42.2	6
CFS7	70C+20F+7.5M	3.4	6.2	46.6	6.1
CFS8	72.5C+20F+10M	3	5.6	46.9	6.1
CFS9	67.5C+30F+2.5M	2.4	6.3	44	5.8
CFS10	65C+30F+5M	3.4	4.1	45.1	6.6
CFS11	60C+30F+7.5M	3.1	4.5	47.4	7.1
CFS12	62.5C+30F+10M	2.8	6	50.4	6.9
CW1	90C+10W	2.5	10	39.9	5.8
CW2	80C+20W	5.4	5.4	41.9	5.1
CW3	70C+30W	10.2	4.2	39.8	6.3
CWS1	87.5C+10W+2.5M	6.2	2	39.3	5.7
CWS2	85C+10W+5M	9	4.1	40	5.9
CWS3	82.5C+10W+7.5M	2	2.1	40.5	5.9
CWS4	80C+10W+10M	7.1	5.8	43.2	5.7
CWS5	77.5C+20W+2.5M	2.9	5.6	46.2	6.3
CWS6	75C+20W+5M	4.9	4.4	47.4	6.4
CWS7	72.5C+20W+7.5M	5.8	2.9	50.2	6
CWS8	70C+20W+10M	4.4	2.5	55.4	6.2
CWS9	67.5C+30W+2.5M	2.8	8.6	40.7	5.4
CWS10	65C+30W+5M	7.5	5.6	44.1	4.7
CWS11	62.5C+30W+7.5M	5.3	5.8	45.9	6
CWS12	60C+30W+10M	4.9	6.1	46.3	5.5
Cwf	90C+5F+5W	2.9	8.8	41	5.8
CwfS1	87.5+5F+5W+2.5M	2.5	7.9	41.6	6
CwfS2	85+5F+5W+5M	3.1	7.6	46.3	6
CWf	85+5F+10W	2.2	10	40.2	5.9
CwF	85+10F+5W	2.3	127	40.2	5.1
CwFS1	82.5+10F+5W+2.5M	2.4	128	41.5	5.5
CWfS1	82.5+5F+10W+2.5M	2.3	3	36.7	5.5
CwFS2	80+10F+5W+5M	2.9	7.4	42.6	6
CWfS2	80+5F+10W+5M	3	7.2	48.4	5
CWF	80+10F+10W	3.7	4.5	45.3	6.3
CWFS1	77.5+10F+10W+2.5M	3.1	4.6	47.8	6.4
CWFS2	75+10F+10W+5M	4.5	6.1	46	8.6
CWFS3	72.5+10F+10W+7.5M	2.9	9.2	45.9	5.6
CWFS4	70+10F+10W+10M	3.6	7.1	46.4	5.8

TABLE 2. Mix design of normal PQC

Normal PQC of flexural strength 4.5MPa used for SCC trials as per IRC 44 (Quantity in kg/cum)				
C	F.A.	C.A.	W	Nominal MSA=16mm
45	711	1057	165	Superplasticizer 0.3% ~1.23lt/cu m.
1	1.58	2.35	0.36	
CA:FA=60:40				
Quantity ratio of 20mm:10mm=70:30				
Assuming that 20% cement reduction takes place on addition of superplasticizer				

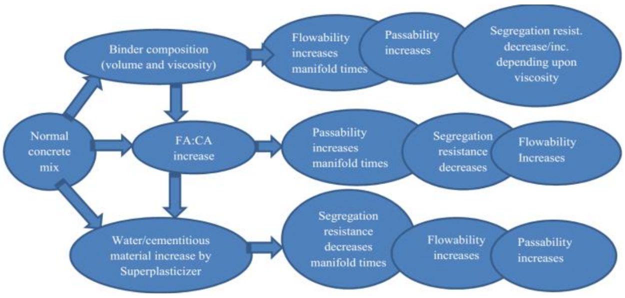


Figure 1. Sequential steps in yielding a SCC from a normal concrete

There are three parameters involved in yielding a SCC which differ from those of a normal concrete. These are binder volume (binder composition), coarse aggregate to fine aggregate ratio, or vice versa, and water to cementitious material ratio. All three parameters, i.e. binder composition, FA: CA and water to cementitious material ratio are required to be changed to increase the flowability and passability of trial concrete. But, the important thing is the order in which they have to be changed. Superplasticizer could not be introduced abundantly to normal concrete initially, or FA: CA cannott be changed without knowing the volumetric change in binder content. Figure 1 shows the effect of altering these parameters in a normal concrete. The effects have been shown in decreasing order of magnitude from left to right. Viscosity enhancing admixture needs to be added in the binder material in order to balance the decrease in segregation resistance caused by the change in other two parameters, otherwise the concrete will segregate, and will leave only water separated from other constituents. Trials indicate that the increment needed in FA: CA is proportional to the volumetric increase in binder material. Increasing binder volume without increasing the FA: CA, causes lesser passability whereas if FA:CA is increased blindly for a constant binder composition, then a segregated mix is obtained having cement laitance. Increasing water to cementitious material ratio by addition of superplasticizer, increases both flowability and passability, but it imposes a high danger of segregation in which the coarse aggregates leave the mortar.

3. TESTING OF MIXES

The testing program initially consists of general tests to check the physical and chemical composition of materials. This includes particle size analysis, surface area analysis, and X ray fluorescence spectrometery (XRFS). Particle size analysis was performed using Ankersmid laser diffraction based analyser. Blaine's air permeability for cement and BET permeability test was performed for all other admixtures used in this study. Chemical composition was found by XRFS test. Hydrated products of the pastes and their compositions were studied through images obtained from scanning electron microscopy (SEM) technique and X-Ray diffraction tests, respectively. Second stage of testing consisted of workability, permeability, and drying shrinkage test on high flow concrete mixes. Workability characteristics like flowability, passability and segregation resistance were evaluated with the help of Abrams cone & V funnel, J Ring, and probe ring, respectively (Figure 2). Permeability and drying shrinkage were tested as per IS 3085 and ASTM C1581, respectively. Poly carboxylate ester (PCE) based superplasticizer was added in increasing volumes, based on PCE/ cement (w/w) ratio, whilst making trial.

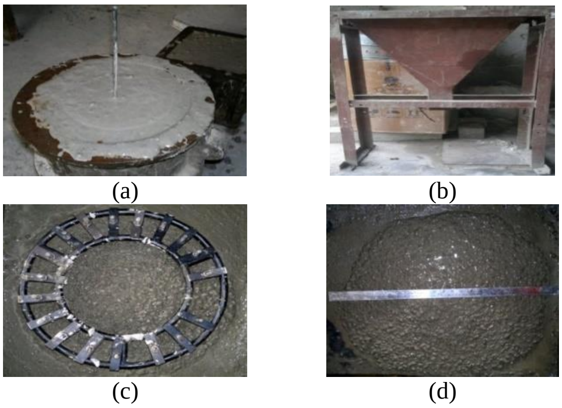

(a) (b)
(c) (d)

Figure 2. Workability tests of concrete mixes (a) probe ring (b) V funnel (c) J Ring & (d) Abram's flow test

4. RESULTS AND DISCUSSION

4. 1. Physical Composition of Powdery Materials

Particle size analysis is shown in Figure 3. Microsilica was finest among all considered powdery materials followed by WMF, fly ash and cement, respectively. The peak of WMF lies exactly in between the peaks of microsilica and OPC. This interpretation clearly infers that WMF used was median size to both microsilica and OPC and hence, an excellent interlocking within these particles is anticipated physically. It is also clearly depicted that OPC used for the study, exhibits particle sizes comparable to fly ash as revealed by the presence of secondary peak in Figure 3. Peak patterns analysis suggests that fly ash and OPC have nearly same size range, but prolonged post peak profile of fly ash indicates that there are numerous fractions of fly ash which are even larger in size than OPC particles. The degree of fineness of microsilica, WMF and fly ash with respect to OPC are 60, 2.8 and 1.3, respectively. Results strongly hinted that microsilica would be prominently proactive in comparison to the rest, as it has inherent ability to contribute strength development through its least surface area.

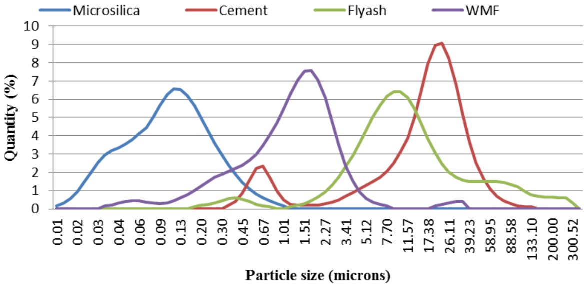


Figure 3. Particle size variation for various materials

4. 2. Chemical Composition of Powdery Materials

Table 3 shows the quantitative results of the amount of oxides present in cement and other admixtures found through XRFS test conducted in accordance with IS: 12803. Following are the few observations drawn from the study:

Fly ash used in the present study contains appreciable amount of silica and highest amount of alumina when compared to the rest of the materials. WMF shares equal amounts of lime & silica, and traces of alumina. Their presence indicates that WMF has tendency for self-cementation and moderate rate of reaction. But by virtue of its crystalline nature, WMF is more inert and serves as excellent pore filler. Microsilica mainly consists of silica, and rest of other oxides are in meagre amount. In its amorphous state, fine microsilica possesses higher surface areas because of which it has greater infilling capacity and reactivity too. Thus, it is apt for reduction of CH and ettringite considerably.

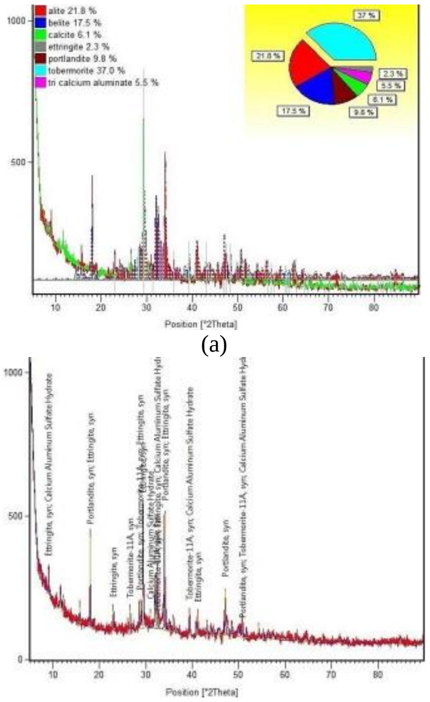
4. 3. XRD Study on Hydrated Pastes

The X-ray diffraction technique was employed to determine the behaviour of different paste mixes at initial stages of hydration. Samples were taken for test after allowing hydration for 14 days. XRD patterns, depicted in Figure 4(a), show the quantitative data of hydrated cement obtained in the form of pi-chart from the XPERT High Score application. Besides quantitative data, labeled peak diagram is shown for cement in Figure 4(b).

Labeled peak diagram of hydrated cement shows that a given peak may correspond to a peak occurring in the diffraction pattern of two or more hydration products. Therefore, simultaneous matching of intensities of different compounds is necessary to find out the quantitative value of a given compound in the hydrated mix.

TABLE 3. Chemical properties of cementitious materials including OPC

Compound	Cement	Fly ash	WMF	Silica fume
SiO_2	20.2	35	48	92.9
Al_2O_3	5.2	26	1.4	0.9
Fe_2O_3	3	8.7	0.6	0.72
MgO	1.51	5	0.2	0.57
SO_3	2.2	3	-	0.16
Na_2O	0.08	1.5	-	0.32
Chloride	0.014	0.005	-	0.037
Loss on ignition	4.3	5	4	2.6
CaO	62.9	15.3	45.9	1.4
K_2O	0.6	0.5	-	0.4



(a)

(b)

Figure 4. (a) XRD profile of cement paste, (b) peak diagram of hydrated products for cement paste

Table 1 provides the composition data compiled in a tabular form for all pastes. Following observations are made from the XRD study:

(i) Results on fly ash with micro silica

With the increase in fly ash content, the rate of chemical reaction tends to increase between 1-3 days. This is apparent from SEM image shown in Figure 5 which shows large levels of freshly formed CSH in the mix CF1 and CF3. Formations of C-S-H gels increase with the increase of fly ash inclusion, and on the other hand, there is considerable reduction in CH formation. SEM images referred in literature verify this phenomenon [10]. It has also been observed that inclusion of fly ash slightly generates more C_3A and ettringite compounds as can be seen from Table 1. For 2.5% -5% microsilica content the rate of C-S-H formation was lesser in comparison to that beyond 5% as there is considerable change in matrix pores for the two sets. In later mixes, fly ash facilitates more water to microsilica owing to high water release caused by deflocculating of cement particles on account of repulsion caused by bigger negatively charged fly ash particles. One more reason is the ball bearing effect caused by smooth round fly ash particles.

(ii) Results on WMF with micro silica

Microsilica with WMF will not react at the same rate because WMF causes lesser water displacement and is not able to orient CH and ettringite to that extent, alike fly ash. Though WMF alone favored a high rate of reaction as opposed to its inert nature, and thus more C-S-H content in the initial period of hydration was observed, but this effect was limited up to only 20% WMF content (Figure 6 shows mixes CW1 and CW3), because beyond it, the cement content in the mix decreased as compared to the normal concrete mix. WMF reduced lime content like fly ash due to good amount of reactive silica present in it, but only fly ash was found to reduce ettringite (needles type product “ettringite” shown in Figure 6(a) representing mix CW1) from the hydrates due to higher amount of less reactive alumina, which went into solution slowly after ettringite formation and converted ettringite into calcium aluminate mono sulphate hydrate.

SEM images of WMF and fly ash admixed concrete as discussed in [11] comply with this fact. Formations of C-S-H gels were almost equal to that of fly ash admixed cement pastes irrespective of their contents. The rate of formation of C-S-H compounds gradually increased as the dosage of WMF increased for the same microsilica contents, and subsequently CH compounds reduced.

(iii) General results

For binary mixes, maximum C-S-H compounds were observed from CF3 (70%C: 30% F) mix followed by CW2 (80%C: 20%W), CF2 (80%C:20%F), CW1 (90%C:10%W), CW3 (70%C: 30%W), and CF1 (90%C:10%W) respectively. Similarly for ternary mixes, maximum C-S-H compounds were produced by CWS8 (70%C: 20%W: 10%M), followed by CFS12 (62.5%C: 30%F: 10%S), CWS7 (72.5%C: 20%W: 7.5% S), CFS11 (60%C: 30%F: 7.5%S) & CWS6 (75%C:20%W:5%S), respectively. In combined mixes maximum C-S-H was produced by CWfS2 followed by CWFS1, CWFS4, CwfS2 and CWS12, respectively. Microsilica addition shortened the dormant period and increased the acceleration of hydration after dormant period. Therefore, an increase in C-S-H content was found with increase in microsilica content both for fly ash and WMF substitution (Figure 7 shows mixes CWS4 and CFS4).

Nochaiya et al. [12] also verified that use of fly ash with microsilica increase C-S-H formation in concrete.

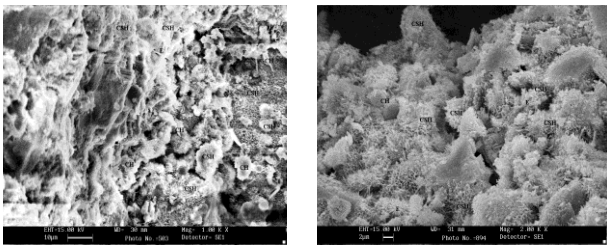

(a) (b)

Figure 5. (a) SEM image of CF1 & (b) CF3

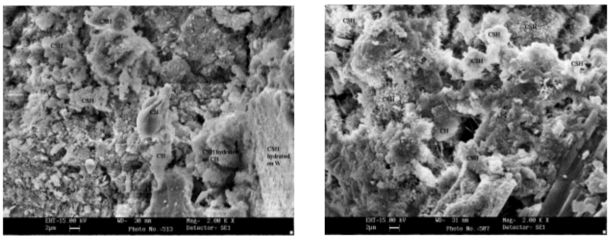

(a) (b)

Figure 6. (a) SEM image of CW1 & (b) CW3

Microsilica increases the hydration rate and reduces the lime content at a higher rate than other admixtures, but it can’t control growth of ettringite because of its lower alumina content.

4. 4. Drying shrinkage resistance of concrete mixes This test corresponds to the behaviour of concrete in the period before 28 days, and thus the behaviour of concrete in the first seven days has more prominent effect on the drying shrinkage of concrete. Typical concrete shrinkage has been measured at 520 to 780 millionths. Table 4 shows the cracking time and final stress rate for different mixes. While testing at laboratory, shrinkage is measured by two parameters: stress rate due to shrinkage and time for crack development. Both of these parameters vary according to paste composition (fineness), which affects the continuity of pores in hardened paste as well as the rate of hydration.

It is not sufficient enough to say that the shrinkage of a concrete would be higher, if it contains larger fraction of fine materials. This would be true to say only, if the water adsorbed by the particle at the capillary voids is not held strongly, if the particle is not able to convert the capillary voids into gel pores, and if the pores are continuous. All of these factors are dependent upon the size and reactivity of the particle.

(i) Results on WMF with microsilica

Soliman and Nehdi [13] have also suggested that there is a reduction in total shrinkage with increasing content and aspect ratio of WMF. It was suggested that as the WMF content increased from 4 to 12%, the reduction in total shrinkage at 7 days increased from 11 to 16% for very fine microfibers and from 2 to 9% for medium fine microfibers, with respect to that of the control mixture.

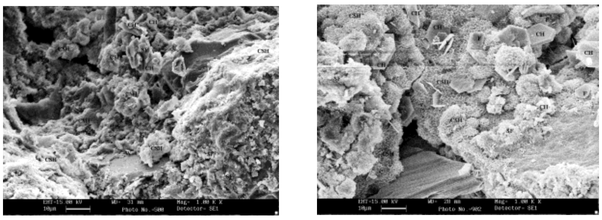


Figure 7. (a) SEM image of CWS4 & (b) CFS4

TABLE 4. Results obtained from the restrained shrinkage test

Mix	Max. µStrain	Initial age (Days)	Age at max. strain (Days)	Strain rate (α) at elapsed time T ($\varepsilon=\alpha\times T^{½}+K$)	Avg. µ strain rate (α)	Time at max. strain (T_r Days)	Stress rate (q) MPa at T_r	Cracking potential
C	-96	0.24	12.31	Y=10.48X-58.35	10.48	12.06	0.109	Mod High
CW1	-70	0.03	18.85	Y= 6.872X-37.00	6.87	18.82	0.057	Mod Low
CW2	-55	0.25	16.81	Y= 4.836X-35.12	4.83	16.56	0.043	Mod Low
CW3	-96	0.24	23.69	Y= 9.069X-54.14	9.07	23.45	0.068	Mod Low
CWS1	-56	0.47	28.00	Y= 10.95X+0.280	10.95	27.52	0.075	Low
CWS2	-64	0.34	19.54	Y= 5.266X-42.20	5.27	19.19	0.043	Mod Low
CWS3	-68	0.34	22.51	Y= 9.956X-17.54	9.96	22.17	0.076	Mod Low
CWS4	-67	0.50	27.40	Y=11.13X-2.352	11.13	26.89	0.077	Low
CWS5	-72	0.26	18.78	Y= 4.316X-51.34	4.32	18.51	0.036	Mod Low
CWS6	-70	0.55	26.59	Y= 2.317X-56.68	2.32	26.03	0.016	Low
CWS7	-78	0.47	23.69	Y= 4.856X-51.09	4.86	23.21	0.036	Mod Low
CWS8	-76	0.27	20.50	Y= 5.390X-51.34	5.39	20.23	0.043	Mod Low
CWS9	-39	0.40	28.02	Y= 8.081X+6.033	8.08	27.63	0.056	Low
CWS10	-40	0.55	28.02	Y= 6.505X-3.328	6.51	27.47	0.045	Low
CWS11	-54	0.34	24.13	Y= 10.69X-1.725	10.69	23.79	0.079	Mod Low
CWS12	-55	0.34	28.02	Y= 12.36X+3.933	12.36	27.68	0.085	Low
CF1	-120	0.32	14.44	Y= 12.05X-68.02	12.05	14.13	0.116	Mod Low
CF2	-96	0.44	18.92	Y= 15.07X-22.94	15.07	18.49	0.127	Mod Low
CF3	-113	0.42	16.01	Y= 15.59X-52.78	15.59	15.59	0.143	Mod Low
CFS1	-117	0.37	19.17	Y= 12.09X-58.50	12.09	18.80	0.101	Mod Low
CFS2	-116	0.45	20.53	Y= 10.28X-66.31	10.28	20.08	0.083	Mod Low
CFS3	-119	0.29	16.64	Y= 12.05X-69.14	12.05	16.35	0.108	Mod Low
CFS4	-116	0.27	15.04	Y= 11.82X-67.93	11.82	14.77	0.111	Mod Low
CFS5	-84	0.55	28.02	Y= 16.22X+4.654	16.22	27.47	0.112	Mod Low
CFS6	-89	0.34	28.02	Y= 16.03X-2.588	16.03	27.68	0.110	Mod Low
CFS7	-69	0.53	28.02	Y= 13.61X+12.02	13.61	27.49	0.094	Low
CFS8	-95	0.34	28.02	Y= 18.55X+5.899	18.55	27.68	0.127	Mod Low
CFS9	-96	0.50	28.02	Y= 16.42X+0.420	16.42	27.52	0.113	Mod Low
CFS10	-105	0.29	18.02	Y= 11.88X-54.38	11.88	17.73	0.102	Mod Low
CFS11	-108	0.29	21.81	Y= 16.85X-22.19	16.85	21.52	0.131	Mod Low
CFS12	-110	0.45	26.95	Y= 18.88X-2.764	18.88	26.50	0.132	Mod Low
Cwf	-76	0.27	14.47	Y= 7.605X-46.21	7.61	14.20	0.073	Mod Low
CwfS1	-76	0.40	16.64	Y= 6.482X-49.37	6.48	16.24	0.058	Mod Low
CwfS2	-71	0.24	15.04	Y= 5.457X-49.47	5.46	14.81	0.051	Mod Low
CWf	-64	0.29	16.64	Y= 8.414X-28.14	8.41	16.35	0.075	Mod Low
CwF	-74	0.26	15.75	Y= 9.378X-39.02	9.38	15.49	0.086	Mod Low
CwFS1	-71	0.27	20.50	Y= 8.999X-27.76	9.00	20.23	0.072	Mod Low
CWfS1	-70	0.26	16.59	Y= 7.426X-38.48	7.43	16.32	0.066	Mod Low
CwFS2	-63	0.32	15.72	Y= 8.410X-27.03	8.41	15.41	0.077	Mod Low
CWfS2	-52	0.32	16.61	Y= 4.885X-31.74	4.89	16.29	0.044	Mod Low
CWF	-72	0.26	21.78	Y= 8.879X-36.05	8.88	21.52	0.069	Mod Low
CWFS1	-69	0.32	27.84	Y= 10.44X-16.57	10.44	27.52	0.072	Low
CWFS2	-59	0.55	27.84	Y= 10.26X-0.818	10.26	27.29	0.071	Low
CWFS4	-69	0.47	26.93	Y= 11.56X-2.457	11.56	26.45	0.081	Low

Microfibers delay the coalescence and propagation of cracks at early age through better stress transfer at microcracks [14, 15]. On the other hand, the increase in the cracking age with increasing microfiber content implies a higher crack-bridging efficiency and ability of larger size WMF microfibers to overcome the reduction in matrix strength induced by dilution effect. Initially when WMF is added in lower quantity up to 20%, the cement particles are not far apart in the solution, and the voids in between them are easily filled or blocked by WMF due to its pore size or grain size refinement, represented by dense zigzag hydrated WMF particles in the SEM image shown in Figure 6(a). Though the water is released when WMF enters into the cement voids, but this water only is used in the accelerated hydration done by cement particles. As a result of which the water is not able to escape from the pores (mainly gel pores) and shrinkage is reduced. With the increment in the content of WMF in the mix, the cement particles increase their distance, and more and more WMF particles enter into the pore solution present in between these voids. As a result, the number of capillary spaces increase whereas the gel pores reduce. This is verified from the SEM images of mixes containing WMF, as has been shown for CW3 in Figure 6(b). Since the void space is larger, the initial hydration, as well as insufficient capacity to block the voids, provided by WMF, is not sufficient to stop the water from escaping from these capillary voids. Therefore, an increased shrinkage stress was reported for WMF content greater than 20%. As a reinforcer, WMF will increase the tensile strength and toughness of mortar, which would resist the crack development and also will delay the propagation of cracks by distributing the stresses over a local region. Thus, the overall effect observed for WMF addition, was the delay in crack development in spite of high stress rate. Since the time period of cracking also depends upon the stress rate development, therefore the variation trend for time period of cracking is similar to the stress development.

(ii) Results on Fly ash with micro silica

Idorn & Thaulow [16] suggested that coarser fly ash particles act as micro aggregates which reduce the shrinkage, increase the packing of aggregates with the paste and thus increase the tensile strength, increase the density of the concrete, thereby leading to reduction in crack propagation and porosity, causing a direct increase in compressive strength and stiffness. Also this portion of fly ash, absorbs water in capillary pores due to surface tension and holds it for long time hydration [17]. Hence, when microsilica is present, the unreacted coarser fly ash at later ages avail the water to the microsilica, and cause its hydration, thereby increasing the strength of the concrete. An excessive fly ash beyond 30% of total cementitious material has been found to reduce strength due to dilution of cement and increment in porosity cause by its coarser particles [18]. For fly ash mixes, the hydration rate is higher than normal concrete uptil 7 days. The effect of this acceleration increases its crack development time in comparison to normal cement concrete. After 14 days the effect of acceleration diminishes and the samples start cracking (Figure 8 showing minute cracks formation in mix CFS4). Though fly ash contains alumina and calcium oxide which promote ettringite formation in presence of sulphates, but the consumption of lime due to fly ash hydration may hinder the formation of ettringite. Also, the reactivity of alumina depends upon whether it is available in glass part of the compound or not [18]. If it is present in glass part, then it provides a long term source of ettringite formation in presence of sulphates. The reactivity of fly ash as noticed from the XRD test suggests that ettringite formation is hindered in presence of fly ash. This suggests that fly ash does not contain reactive alumina and highly neutralizes CH; if it did, then ettringite formation would have been promoted rather than hindered. Thus, the stress rate is equal to or a bit higher than normal concrete because effect of pore refinement is nullified by presence of fine material (fraction of fly ash much finer than cement) verified by particle size analysis. Hence, with the increment in fly ash content, both the stress rate and the crack time increase to a small extent. From the results obtained, it has been found that WMF mixes has the highest stress rate increment capacity and its crack development time is followed by microsilica. Microsilica has maximum stress rate reduction capacity due to higher paste strength imparted by high rate of hydration. Fly ash has the lowest crack time increment capacity. Cohen et al. [19] studied the influence of microsilica on bulk paste modification and pressed that excessive fine cement promotes rapid hydrations, which is further complemented by microsilica, and thus cause expansion of concrete. On loss of water, this expanded concrete starts shrinking, but the restraint offered by concrete on account of high strength provided by microsilica as well as the pore discontinuity provided through filler effect and pore refinement controls the shrinkage. The results of present study are thus in agreement with this study.

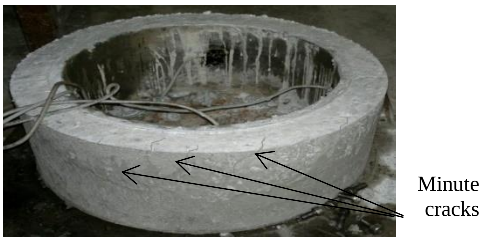


Figure 8. Crack development in Mix CFS4 after 14 days during Ring Shrinkage test

4. 5. Permeability of Concrete Mixes At a water-cement ratio of 0.45, the coefficient of permeability is typically 10-11 or 10-12 m/s; permeability of an order of magnitude lower than this range is considered to represent concretes with a very low permeability. Thomas et al. [20] have suggested that group of admixtures taken together to form a ternary blend offered better resistance to permeability and penetration of chloride ions. Comparative results with respect to normal concrete have been presented in Figures 9, 10 and 11 for binary, ternary and combined concrete mixes, respectively. Figure 9 clearly depicts that coefficient of permeability of concrete decreases as the percentage of fly ash and WMF part replacement increases. The percentage reductions are 14.13, 32.07 and 37.23% when fly ash was admixed at 10, 20 and 30%, respectively with respect to that of normal concrete. Similarly, for WMF admixed concretes they are 48.33, 50.15 and 59.12%, respectively with respect to normal concrete. Least coefficient of permeability is being offered by CWS12 followed by CWS8, for WMF and microsilica admixed concrete. Similarly, for fly ash and microsilica admixed concrete, CFS12 offered the least coefficient of permeability followed by CFS7. Their percentage reductions are 98.52, 89.24, 88.09 and 81.16%, for CWS12, CWS8, CFS12 and CFS7, respectively. But if we look at the combined concrete mixes performances shown in Figure 11, maximum resistance against permeability of water is being offered by CWFS4 followed by CWfS2, CWFS3 and CWFS2; only four top mixes are considered. Their percentage reductions are 87.61, 85.71, 85.33 and 84.04%, respectively with respect to that of normal concrete. Permeability is highly influenced by degree of packing, which is promoted by the following:

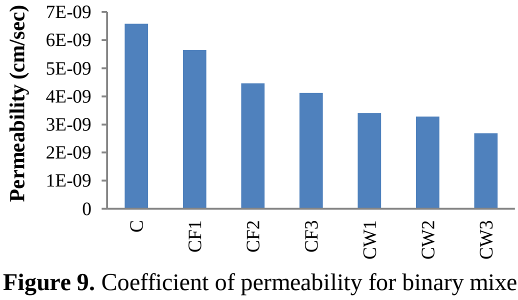


Figure 9. Coefficient of permeability for binary mixes

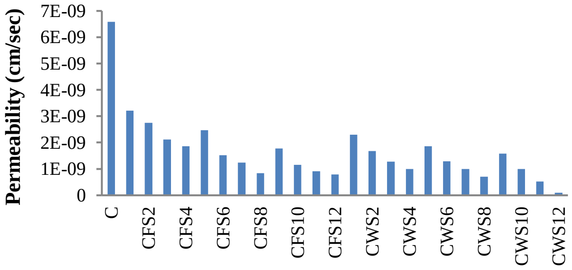


Figure 10. Coefficient of permeability for ternary mixes

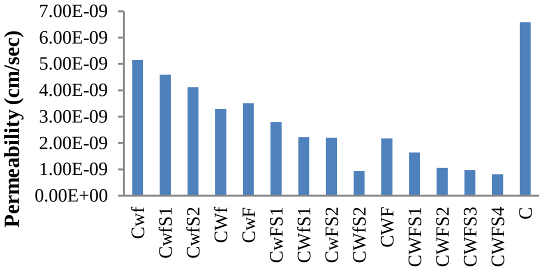


Figure 11. Coefficient of permeability for combined mixes

(i) Microsilica content above 5% is necessary at the interfacial transition zone (ITZ: zone between mortar and coarse aggregates) and in the rest of matrix for all mixes.

(ii) WMF and fly ash in either in equal proportions, combined weightage of 15-20%, or WMF in higher proportions is necessary to fill the voids in between cement particles.

5. CONCLUSION

Following conclusions could be drawn from the results obtained in this study:

1. There is a specific order in which the parameters required for obtaining SCC are to be changed. FA:CA ratio has to be increased in direct proportion to the increment in ratio of binder volume after and before addition of admixtures.
2. Drying shrinkage is generally low for mixes containing 20% of pozzolanic admixture and 5% of microsilica. Quaternary/combined mixes containing WMF and fly ash in equal proportions showed least drying shrinkage because of three factors namely: active hydration rate, reduced capillary voids and expansion of fine materials. In general, drying shrinkage reduced by 49 and 36.6% for WMF-microsilica and combined mixes, respectively, whereas for fly ash-microsilica mixes, an increment of 1.25% was observed.
3. Permeability is least for ternary mixes containing maximum amount of either fly ash or WMF, and quaternary mixes containing WMF and fly ash in equal proportions. Hence, it shows that permeability significantly depends upon capillary voids rather than ITZ especially for concrete mixes containing extra fine material. The permeability of the mixes decreased by 82, 74 and 61.5%, respectively for WMF-microsilica, fly ash-microsilica and combined mixes.

Based on the above analyses, WMF-microsilica mixes were found to offer better properties of SCC. Mixes that contain lesser amount of fines do not show good correlation between drying shrinkage and permeability, whereas for the mixes that contain higher amount of fines maintain fair correlation between the aforesaid properties.

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Comparison of Permeability and Drying Shrinkage of Self Compacting Concrete Admixed with Wollastonite Micro Fiber and Fly Ash

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چکیده

انتخاب جایگزینی برای سیمان در بتن خود تراکم (SCC) برای حفظ محیط زیست، کاهش هزینه و استفاده از مواد زائد حائز اهمیت است. این مقاله بر روی مقایسه نفوذ پذیری و آب‌رفتگی SCC که حاوی میکرو فیبر Wollastonite (WMF)، که فیبری پوزولانی ارزان در مقایسه با خاکستر بادی است، تمرکز دارد. میکروسیلیکا نیز به منظور ایجاد گران‌روی مورد نیاز برای حفظ همگنی مخلوط اضافه شد. آزمایش‌های لازم برای بررسی جریان‌پذیری، عبورپذیری (روانی) و مقاومت در مقابل جدانشینی در مخلوط‌های دوتایی، سه‌تایی و ترکیبی از مواد هم‌گیر انجام شد. نتایج نشان داد که آب‌رفتگی بتن مسلح حاوی WMF به میزان ۴۹٪ کاهش یافته، در حالی که برای بتن معمولی حاوی خاکستر بادی ۱,۲۵٪ افزایش یافته است. ضریب نفوذ پذیری برای این دو حالت به ترتیب ۸۲٪ و ۷۴٪ کاهش یافته است. حفره‌های مویینگی بر نفوذ پذیری بتن سخت‌شده تاثیر گذاشت، اما آب‌رفتگی به طور عمده تحت تأثیر افزایش مقاومت کششی قرار گرفت. به طور مشخص، خاکستر بادی یک افزودنی قابل اعتمادی برای کنترل آب‌رفتگی بتن‌های روان نیست.

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