International Journal of Transportation Science and Technology 9 (2020) 170–181

Contents lists available at ScienceDirect

International Journal of Transportation Science and Technology

journal homepage: www.elsevier.com/locate/ijtst

Behavioral study of self-compacting concrete with wollastonite microfiber as part replacement of sand for pavement quality concrete (PQC)

Abhishek Jindal [a,*], G.D. Ransinchung R.N. [b], Praveen Kumar [b]

[a] Department of Civil Engineering, Central University of Haryana, Mahendergarh, India
[b] Department of Civil Engineering, Indian Institute of Technology, Roorkee 247667, India

ARTICLE INFO

Article history:
Received 14 November 2018
Received in revised form 24 May 2019
Accepted 19 June 2019
Available online 19 July 2019

Keywords:
Self-compacting concrete
Wollastonite micro-fiber
Slump flow
Compressive strength
Flexural strength

ABSTRACT

The fact that self-compacting concrete (SCC) does not require any supplementary compaction to fill in every nook and corner of the structure without compromising with strength and durability makes it much more futuristic and desirable over conventional concrete. Present study highlights the behavioural changes in SCC for PQC applications at macro and micro levels with the incorporations of wollastonite micro-fiber; proposed to be used for restoration of deteriorated pavement quality concrete slab. Wollastonite micro-fiber was incorporated as part replacement of fine aggregates in proportions of 10–50% with an offset of 10%. Different properties of SCC mixes such as flow-ability, segregation resistance and filling ability were investigated in fresh state while mechanical properties including compressive strength, flexural strength and hardened density were studied in hardened states. The SCC mixes were also investigated for estimating effect of incorporating wollastonite micro-fiber in hydrated states of cement mortar. Inclusions of wollastonite micro-fiber in SCC enhanced the cohesiveness of the mix thereby improving the density and reducing its water absorption. SCC mixes with wollastonite micro-fiber showed higher flexural and comparable compressive strength parameters than those of conventional SCC mix. SCC mix with 30% wollastonite micro-fiber as a replacement of fine aggregates provides similar strength and better repair prospects as compared to conventional SCC or normal concrete mix.

1. Introduction

Self-compacting concrete as the name suggest is a concrete which does not required any external compaction and fills in the formwork by virtue of its self-flowing behavior. This property makes its application widely acceptable in structures with congested reinforcements where compaction otherwise would be a strenuous task. Apart from the benefits of self-leveling,

Abbreviations: SCC, self-compacting concrete; OPC, Ordinary Portland Cement; SEM, Scanning Electron Microscopy; IRC, Indian Road Congress; IS, Indian Standards; ITZ, Interfacial Transition Zone.

Peer review under responsibility of Tongji University and Tongji University Press.

* Corresponding author.
E-mail address: ajindal@cuh.ac.in (A. Jindal).

https://doi.org/10.1016/j.ijtst.2019.06.002
2046-0430/

SCC upon drying provides a shiny surface, which needs very little finishing. The basic difference from conventional concrete is that SCC has higher amount of super plasticizer; aggregate mixture, proportional in size to provide locking tendency to achieve desired compactness and altered fluid properties to deliver a cohesive mix.

According to European Project Group (EPG) (2005) self-compacting concrete could be defined as "concrete that has ability to flow under its own weight thereby completely filling the formwork in the presence of dense reinforcement, without compromising with homogeneity and needing any external compaction". In words of Gesoglu et al. (2009), SCC is characterized by its high flow-ability property that is achieved by employing high cement content and by using high-range water-reducing admixture.

Although the origin of SCC is debatable, Japanese researchers claims that self-compacting concrete was initially devised in 1980s in order to compensate for lack of durability resulting from improper compaction of concrete, owing to shortage of skilled labour in Japan. Ouchi (1999) discussed that Okamura who recognized this deficit created the first SCC prototype in 1986, which did not require any aided compaction. Collepardi (2003) however, discussed the use of SCC for commercial applications in Europe, Asia and United States in early 1980s. Tanaka et al. (1993) highlighted the construction of Akshi Kaikyo bridge in Japan as a pioneering work with the application of SCC.

The drawback of SCC is its higher cost when compared with conventional concrete due to involvement of expensive chemical admixture and cement in large quantity. Hence, material engineers are persistently looking for suitable low cost materials. As on today, in general practice, inert and / or reactive mineral additives are often incorporated as low, medium or high volume cement replacements to bring down the cost of SCC.

Few researchers have worked on SCC using fly ash and silica fume as mineral additives and they are reported to exhibit pozzolanic characteristics i.e. they have free silica and alumina, which during hydration participates in reactions thereby increasing the products of hydration. Dinakar et al. (2008) reported lower strength grade concrete (20 MPa–30 MPa) on replacing 70%–85% (volume/volume) of cement with FA, while higher strength grade concrete was reported for lower replacement (30%–50% volume/volume) levels. Gutha (2010) reported an increase of 99% in 7-day compressive strength for SCC mix with 15% replacement of fine aggregates by fly ash. Several other researchers such as Groth and Nemegeer (1999), Khayat and Roussel (1999), Massicotte et al. (2000), Grünewald et al. (2001), Bui et al. (2003, 2005), Corinaldesi and Moriconi (2004), Busterud et al. (2005), Dehn (2005), (Sahmaran et al. (2005, 2007) and Suter and Butschi (2001) have also studied and reported similar results with SCC. Bui et al. (2003) suggested that content of fine material should be increased in mix such that the coarser aggregate particles get layered upon by mortar. Also the amount of paste should be sufficient enough to fill in the voids between aggregates and fibers. Furthermore, it is recommended by Johnston (2001) to reduce the volume of coarse aggregates by at least 10 % when compared with plain concrete to facilitate pumping.

Over the period of time, researchers have pursued studies on SCC mixes using variety of mineral admixtures to evaluate the performance of SCC mixes by part replacing the cement. However, very scanty work has been done towards the use of wollastonite micro-fiber in SCC mix. SCC in the past has been finding applications for structures having dense or congested reinforcements. During repair of concrete pavements (whether partial or full depth repairs) once the concrete is laid, it needs to be compacted properly to fill in the place and provide better bonding with existing pavement. This could be easily achieved by SCC mix owing to its self-flowing property. The objective of this study was to study the behavior and performance of SCC mix having wollastonite micro-fiber as a part replacement of fine aggregate; which could be used for pavement restoration applications.

2. Material and mixture proportions

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) 43 conforming to IS: 8112 was used. The physical and chemical properties of ordinary Portland cement are summarized in Table 1.

Wollastonite is a naturally occurring mineral having fibrous structure which is formed upon the interaction of silica and limestone in hot magmas. The white mineral having acicular shape has high elastic modulus and is generally used as filler in paints or in ceramic industry to reduce shrinkage cracks.

Table 2 presents the chemical and physical properties of wollastonite micro-fiber. The mean grain size of wollastonite micro-fiber was reported to be about 4.5 times finer than OPC (Ransinchung et al. 2009). Figs. 1 and 2 show the OPC and

Table 1
Chemical and physical properties of OPC *Wollastonite micro-fiber*.

	Composition (%)								Specific gravity	Surface area (cm^2/g)	Appearance	Material retained on 45-micron sieve
OPC	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_2	K_2O	Na_2O				
	21.87	6.46	2.90	61.3	2.94	0.54	0.30	0.58	3.13	312.1	Gray	13.0

Table 2
Chemical and physical properties of wollastonite micro-fiber.

CaO	SiO_2	Al_2O_3	Fe_2O_3	Specific gravity	Surface area (cm^2/g)	Appearance	Material retained on 45-micron sieve
45.60	48.00	1.40	0.60	2.90	842.7	Off-white	3.2

Fig. 1. Ordinary Portland Cement.

wollastonite micro-fiber in their amorphous conditions. The particle size and shape of OPC and wollastonite micro-fiber were determined using SEM images as shown in Figs. 3 & 4 respectively.

2.1.2. Aggregates and water

SCC needs to be lean and cohesive at same time, this requires aggregates to be smaller in size and maintain size proportionality to avoid segregation and bleeding. Crushed granite having nominal maximum size of 10 mm & 6 mm were used in the present investigation as coarse aggregates. Riverbed sand having fineness modulus of 2.69 conforming to grading zone-II as per IS: 383 were selected as a fine aggregate. In addition to riverbed sand, wollastonite micro-fiber was incorporated as a fine aggregate by part replacing the sand. Potable water conforming to IS: 456 were used for casting concrete samples as well as for curing purpose throughout the investigation.

2.1.3. Chemical admixtures

In order to obtain SCC having desired flow-ability and T500 duration, a super plasticizer was used for water tightness and workability retention. Water reducing chemical admixture conforming to IS: 9103 was used in the present investigation. The specific gravity of chemical admixture was 1.260 at 27 °C and air entrainment was reported to be less than 1.5%. The chemical admixture was reported to be free of chloride content.

3. Mixture proportion

Initially, conventional concrete mix design was carried out to ascertain the constituents of concrete as per the Indian Roads Congress standard (IRC: 44), which is specially formulated for pavement quality concrete. Eventually, the content

Fig. 2. Wollastonite micro-fiber.

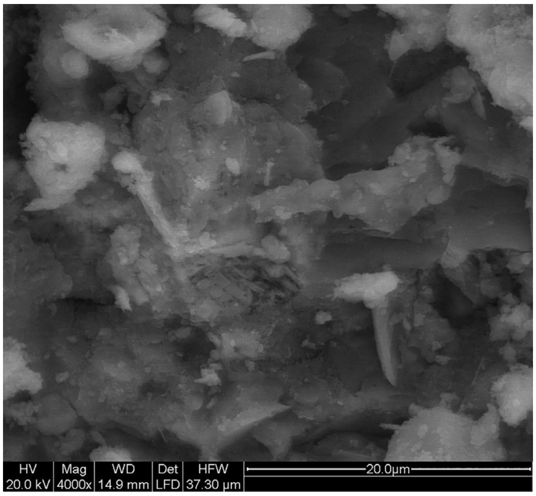

Fig. 3. SEM image of OPC.

of solid material in SCC was arrived through iterative processes by way of measuring the slump flow test. The test method is very similar to the conventional Indian standard (IS: 1199) slump test of fresh concrete. A truncated cone mould shape having internal dimensions 200 mm diameter at the base, 100 mm at the top and a height of 300 mm was employed for slump flow test. However, instead of measuring the loss in height, the diameter of the spread concrete is measured in two perpendicular directions.

Those SCC mixes having flow diameter more than 600 mm were chosen as satisfactory SCC mixes in the present study. The selected mixture compositions for the present study are presented in Table 3. In the present study, the volume of fine materials was increased up to 50% of the total aggregate content. The replacement of fine aggregates by wollastonite micro-fiber was carried out at different replacement levels ranging from 10% to 50% with an offset of 10% and various parameters associated to the mixes were determined. Mix S0 with 0% replacement level was taken as referral mix.

4. Experimental programme and test procedures

The present study focused on two aspects pertaining to self-compacting concrete. SCC in general has higher finer content and amount of super plasticizer, which supplements the segregation sensitivity of mix. Laboratory study was conducted on fresh SCC mixes to examine the potential of segregation and their flow-ability with or without wollastonite micro-fiber. Secondly, hardened properties of SCC were determined, as compressive strength and flexural strength require greater understanding to permit use of SCC in repair of PQC slabs.

4.1. Tests conducted on fresh SCC mixes

In order to produce an effective SCC complying with the acceptance parameters for fresh SCC, the design mix of SCC was checked for various tests such as slump flow test, V-funnel test and probe test etc.

Fig. 4. SEM image of Wollastonite.

Table 3
Mixture compositions for referral and admixed SCC mixes.

Mix No.	Mix Description	Water Kg/m^3	OPC kg/m^3	Fine materials Kg/m^3		Coarse aggregate kg/m^3		SP Kg/m^3
				Sand	Wollastonite	10 mm	6.3 mm	
S0	100 S	255	425	888.5	0	444.25	444.25	12.75
S1	90 S	255	425	799.65	88.85	444.25	444.25	12.75
S2	80 S	255	425	710.8	177.7	444.25	444.25	12.75
S3	70 S	255	425	621.95	266.65	444.25	444.25	12.75
S4	60 S	255	425	533.1	355.4	444.25	444.25	12.75
S5	50 S	255	425	444.25	444.25	444.25	444.25	12.75

Slump flow and V-funnel tests were conducted to ascertain the filling ability of SCC and the degree of segregation of self-compacting concrete respectively. The tests set up used in the laboratory study are shown in Figs. 5 and 6 respectively. In addition to these tests, segregation probe proposed by University of Illinois at Urbana-Champaign (UIUC) was also conducted and its typical schematic diagram is shown in Fig. 6.

4.1.1. Slump flow test

An effective and simple method i.e. slump flow test, was used to analyze the free horizontal flow of mix without any obstructions. Slump flow was evaluated as the mean diameter of concrete flow recorded in two perpendicular directions. For better flow-ability, SCC mixes are expected to have a slump flow value higher than 600 mm. About 6 liter of concrete was prepared as per the predetermined mix proportions for all the four SCC mixes. The base plate and inside of the slump cone was properly oiled and the entire assembly was transferred to a level stable ground and the slump cone was brought to the central part of the base plate and held down firmly. With the help of the scoop, SCC mix was filled into slump cone up to the brim without giving any kind of vibration. Fig. 5 (a & b) shows the slump cone apparatus and slump flow diameter being measured during testing.

The surplus material around the top and bottom of the slump cone was removed with trowel and the apparatus was lifted vertically to allow free flow of SCC mix. A stopwatch was used to record the time taken by mix to reach 500 mm diameter, recorded as T500 time. Efforts were made to produce SCC mixes having 500 mm spread circle in 3–7 seconds. According to (Gibs and Zhu, 1998), a lower time indicates greater flow ability.

4.1.2. V-funnel test

For conducting this test, about 12 litres of concrete was prepared from the predetermined SCC mixes. The apparatus (shown in Fig. 6) was initially oiled and placed firmly on ground. It was ensured to keep trap door closed tightly so as to prevent any leakage from the funnel. A large container was placed underneath for collecting the SCC mix. The fresh SCC mix was filled into the funnel system with the help of a scoop without giving any kind of jerk and vibration. This filling was stop only after SCC mix was filled up to the brim of the funnel and the surplus materials were struck off with the help of trowel. The trap door of the funnel was opened within 10 sec filing of SCC mix and at the same time stopwatch was started. The flow time was recorded on completion of SCC mix discharge. The SCC mixes which could flow out completely from-funnel within 5 minutes was selected for further course of investigation.

4.1.3. Probe test

Self-compacting concrete has minor fraction in majority; this coupled with higher dosage of super plasticizer could generate problems associated with bleeding and segregation. Thus it becomes mandatory to check the designed SCC mix for segregations.

The segregation occurrence for SCC mix was investigated with the help of a segregation probe ring as shown in Fig. 7. The procedure followed for segregation determination involved placing the probe ring on SCC mixes freshly filled in cylindrical mould (150 $\times$ 300 mm). The segregation probe ring was made from a 2.38 mm diameter steel wire, and shaped to have a circular base with a diameter of 100 mm. The probe ring was kept at rest in such position undisturbed for a duration of two minutes. The static segregation occurring within the mix comes to light as the probe ring settles down over the top of aggregate surface. The depth of penetration achieved by probe ring indicates the thickness of mortar paste layer existent over the top of segregated SCC mix thus indicating towards the robustness of the mix.

The contents of mix are mixed in a pan with incremental addition of water after testing the mix for segregation, to examine the mixture's sensitivity to water content. The SCC mixes prepared at different water-cement ratio were tested using probe ring and settlement depth was measured.

4.2. Mechanical properties of SCC

Mechanical properties inclusive of compressive and flexural strength were investigated in accordance with IS 516 to ascertain the strength compliance of SCC mixes in study. A total of sixty four numbers of 150 mm hardened cubical

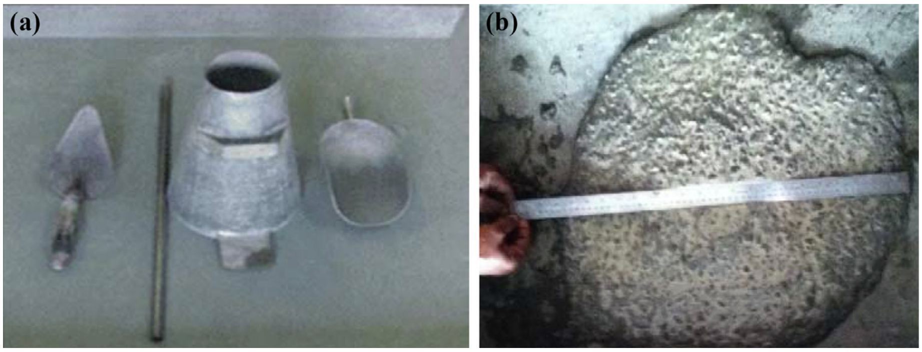

Fig. 5. Test on fresh SCC mixes (a) Slump flow test (b) Spreading diameter.

Fig. 6. V-funnel test.

specimens were prepared and tested for evaluating compressive strength of SCC mix at 7, 14 & 28 days of moist curing from six different SCC mixes including referral SCC. For determining flexural strength, a total of thirty six prismatic specimens having dimensions of 100 mm × 100 mm × 500 mm were prepared and tested destructively. In addition 150 mm cubical specimens were prepared for each SCC mix to determine water absorption of hardened concrete at the ages of 7, 14 and 28 days.

4.3. Scanning Electron Microscopy (SEM) study

The variations occurring in macro properties of concrete are owing to micro level changes incurred in concrete mixes. To understand the changes in behavior of concrete, it is necessary to understand the structure of hydrated hardened cement

Fig. 7. Probe Ring.

paste. Thus understanding of the paste phase becomes more important as it influences the behavior of concrete to a much great extent. Scanning Electron Microscopy allows us to observe the variations occurring at micro levels by providing microscopic views of the object in study. SEM images of hardened cement-mortar admixed with wollastonite micro-fiber after 28 days moist curing were taken and analyzed for the purpose.

5. Results and discussion

5.1. Material characteristics

Material properties results summarized in Tables 1 & 2 shows that wollastonite micro-fiber is 4 times finer and possessed more surface area than that of Ordinary Portland Cement used in study. Also the aspect ratio of wollastonite micro-fiber was found to be more that of cement as evident from SEM images and exhibits smoother texture.

5.2. Fresh SCC mix properties

During the laboratory study, attempts were made to manufacture SCC with or without wollastonite micro-fiber having slump flow of minimum 500 mm spread circle in 3–7 s. All the three trials made for referral SCC mixes with constant water-cement ratio of 0.6 for varied superplasticizer dosages confirmed within the specified ranges (summarized in Table 4). A lower time indicates greater flow ability; hence, for further course of study, the SCC mix having water-cement ratio 0.6 and superplasticizer dosage of 3.0% by weight of cement was chosen.

Similarly, for V-funnel test, the SCC mixes which could flow out completely from-funnel within 5 minutes was selected for further investigations pertaining to mechanical properties of hardened concretes. The patterns observed in Fig. 8 implies that the water-cement ratio selected in the present study was sufficient to resist segregation of SCC mix and maintain desired workability. Table 5 shows that highest slump flow value was offered by referral SCC mix (S0). This flow value decreases when percentage of part replacement of sand by wollastonite micro-fiber increases. The decrease in slump flow values due incorporation of wollastonite micro-fiber with respect to referral SCC mix (S0) were 1.34%, 5.21%, 5.21%, 6.99% and 9.23% respectively for S1, S2, S3, S4 and S5 mix designations. However, these slump flow values were lying well above the minimum specified spread circle diameter and simultaneously cohesiveness of the mix was considerably increased due to incorporation of wollastonite micro-fiber based on visual observations made during experiment. It was also noticed that when sand was part replaced by wollastonite micro-fiber, V-funnel readings and probe readings were slightly more than referral SCC mix. This is attributed to increase in surface area of the SCC mixtures contributed from wollastonite micro-fiber which results in increased cohesiveness of the mix.

5.3. Mechanical properties of SCC

When fine aggregate was partly replaced by wollastonite micro-fiber, an overall gradual reduction pattern in compressive strength of SCC was observed. This strength decrease was more pronounced for mixes with higher contents of wollastonite micro-fiber indicating towards weak bond formation with increase in content of wollastonite as visible in Fig. 9. This is attributed to the fact that wollastonite is finer than sand and thus upon incorporation in concrete are not able to properly fill in the gaps among coarse aggregate particles, thus weak bond and reduction in strength is observed.

Table 4
Summarized results of fresh referral SCC mix S0.

Trial no	W/C ratio	Super plasticizer (%)	T_{500} time (s)	V-Funnel time (s)	Flow diameter Mm
1st	0.60	2.50%	6.3	36	580
2nd	0.60	2.70%	4.6	14	622
3rd	0.60	3.00%	3.4	9	672

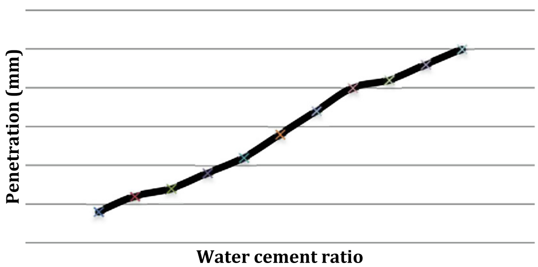

Fig. 8. Settlement depth curve for SCC mixes.

Table 5
Test results for Slump Flow, V-funnel and Probe Values.

Mix No.	Slump flow value (mm)	V-funnel reading (s)	Probe test reading (mm)
S0	672	9	7
S1	663	9	8
S2	651	10	8
S3	637	11	8
S4	625	11	9
S5	610	12	9

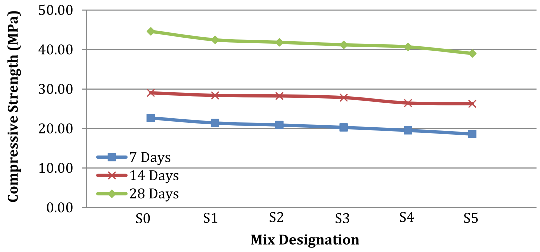

Fig. 9. Compressive Strength trend for SCC mixes.

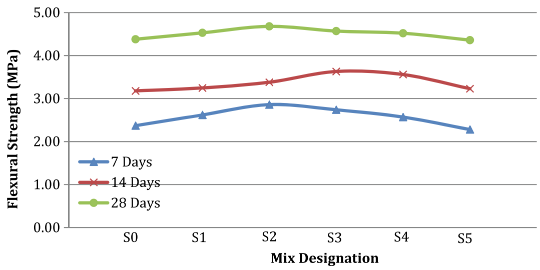

Fig. 10. Flexural Strength trend for SCC mixes.

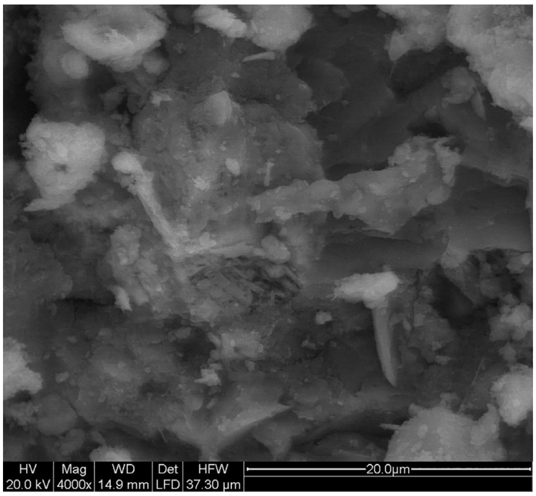

Fig. 11. Cement-mortar paste.

Considerable increase in the flexural strength was observed when fine aggregates were partly replaced by wollastonite micro-fiber. This increase was observed to be significant for mixes with replacement levels up to 30% (shown in Fig. 10) while a gradual reduction in flexural strength was observed when the quantity of wollastonite micro-fiber was increased

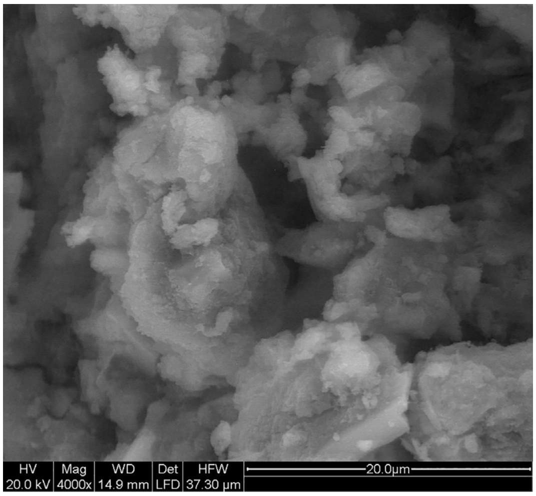

Fig. 12. Cement-mortar mixture containing (10%) wollastonite.

Fig. 13. Cement-mortar mixture containing sand (80%) & wollastonite (20%).

beyond 30%. However, the flexural strength obtained beyond 30% part replacement was almost at par with the flexural strength of referral SCC mix. This increase in flexural strength is attributed to presence of wollastonite micro-fiber in SCC mix, as wollastonite micro-fiber being very fine material and by virtue of being acicular in structure facilitates in better voids infilling capacity and provides better reinforcing effect within the SCC mixture thereby improving the bending strength with its flexible fibrous nature. This mechanism is best explained by SEM images taken for cement-mortar admixed with wollastonite micro-fiber for various replacement levels as depicted in Figs. 9–13.

From this present study it was learnt that fine aggregates could be partly replaced by wollastonite micro-fiber even upto 50% without much compromising the flexural strength of concrete. Densification of the cement-mortar matrix was more pronounced for 20%, 30% and 40% part replacement of sand by wollastonite micro-fiber (Figs. 11–13). It was also noticed that wollastonite micro-fiber have a strong tendency of inducing bridging effect at the transition zone of SCC mix (Fig. 11).

5.4. SEM investigations

SEM images obtained for representative cement mortar paste of different SCC mixes are shown in Figs. 11–16. The SEM investigations highlight the products of hydration obtained for hydrated cement mortar of all the mixes in study. Inclusion of fine particulate wollastonite micro-fibre resulted in more rich and dense concrete mix. This is beneficial from the viewpoint of SCC, which maintains finer content as well as maintaining a mix free from bleeding or other problems. The improvement

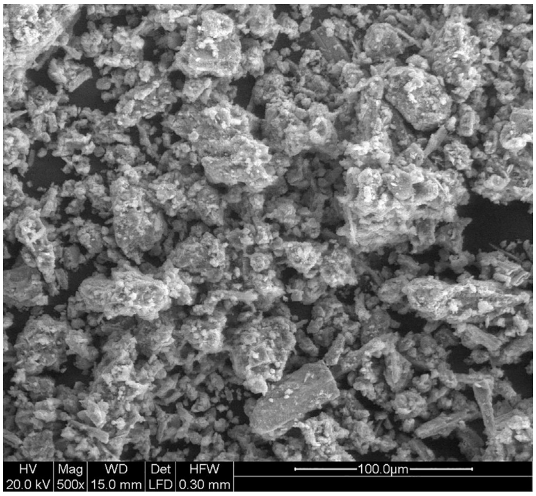

Fig. 14. Cement-mortar mixture containing sand (70%) & wollastonite (30%).

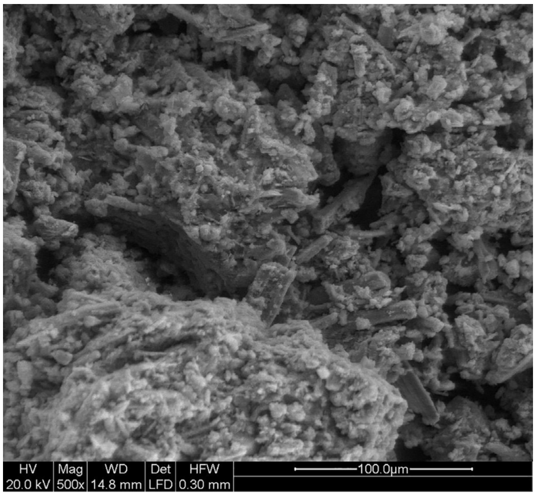

Fig. 15. Cement-mortar mixture containing sand (60%) & wollastonite (40%).

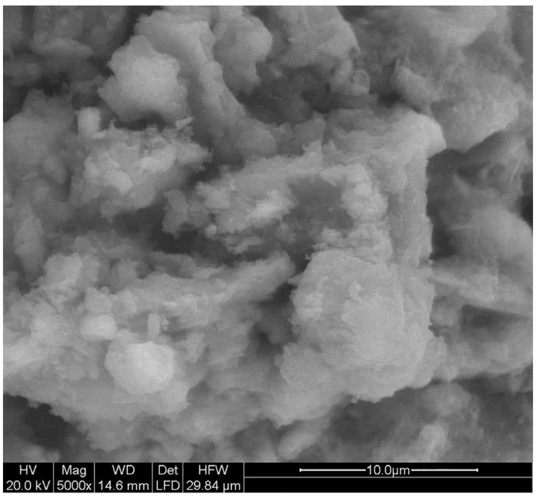

Fig. 16. Cement-mortar mixture containing sand (50%) & wollastonite (50%).

in cohesiveness of concrete mix visible from naked eye has led to improved matrix with lesser voids as visible from SEM images which in turn will has led to strength development in hardened concrete.

Moreover, self-compacting concrete containing wollastonite micro-fibre as visible from SEM images (Figs. 12–16) has visibly more hydration products and less voids in comparison to concrete mix without wollastonite (Fig. 11). As visible from Figs. 14 and 15, presence of fibrous CSH gel and lesser needle type ettringite and voids confirm the pronouncement of hydration products on inclusion of wollastonite micro fibre.

Thus, Wollastonite being much finer than cement improves the cohesiveness and workability of the mix thereby rendering a more flow able concrete, which is desired for SCC.

6. Conclusion

1. Inclusions of wollastonite micro-fiber in SCC mixture exhibit excellent robustness and provide better resistance against segregation as observed from probe test. It was also found that wollastonite micro-fiber can be incorporated up to 50% by part replacing the sand content in manufacturing SCC with improved segregation potential.
2. Part replacement of sand by wollastonite micro-fiber enhances the cohesiveness of the SCC mixture. This enhancement was more pronounced for SCC mix containing 10% wollastonite and more. Segregation tendency was quit prominent for referral SCC mixture and harshness was observed for referral SCC mixture during experiment. Improvement in cohesiveness of SCC mixture was due to inclusion of wollastonite micro-fiber by being very fine and lustrous in nature.
3. For obtaining requisite slump flow diameter and V-funnel time of SCC mix containing wollastonite micro-fiber, required super plasticizer dosage of 3% by weight of cement with water-cement ratio of 0.6 was obtained. Delayed setting was observed for SCC mix containing wollastonite micro-fiber.
4. On admixing wollastonite micro-fiber partly with fine aggregates in self compacting concrete there is gradual decrease in the compressive strength of the SCC mixes when compared to that of referral SCC mix. Similarly, hardened density of SCC containing wollastonite micro-fiber showed lower parameters than that of referral SCC. This is mostly likely due to fact that wollastonite micro-fiber is lighter than fine aggregates which lowers the density of hardened concrete.
5. Gradual reduction in flexural strength was observed when the quantity of wollastonite micro-fiber was increased beyond 30%. However, the flexural strength obtained beyond 30% part replacement was almost at par with the flexural strength of referral SCC mix.
6. Incorporations of wollastonite micro-fibre reduced the water absorption of hardened concrete. This is attributed to better densification of microstructure of the concrete as revealed from SEM study.
7. Wollastonite micro-fiber is a promising material for use in self-compacting concrete as cohesiveness and flowability of concrete increased with its incorporation. Hence, part replacement of fine aggregates by wollastonite micro-fiber is possible upto 30% with added advantage of having higher flexural strength in comparison to referral SCC mix**.**

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank Indian Institute of Technology, Roorkee for providing necessary funding for carrying out the research work.

References

Bui, Van K., Attiogbe, Emmmanuel, (2005). Degussa Admixtures, Inc., Seminar at UM.
Bui, V.K., Geiker, M.R., Shah, S.P., i et al. (2003).. Rheology fiber-reinforced cementitious material. In: RELIM PRO 30 High Performance Fibre -Reinforced Composites HPFRCC4, pp. 221–232.
Busterud, Lars, Johansen, Kåre, Døssland, Åse Lyslo, (2005). ''Production of Fiber Reinforced SCC,'' SCC 2005, Session C-3: Fiber-Reinforced SCC.
Collepardi, M., 2003. Self compacting concrete: what is new? In: Malhotra, V.M. (Ed.), Seventh CANMET/ACI International Symposium on Superplasticizers and Other Chemical Admixtures in Concrete, pp. 1–16.
Corinaldesi, V., Moriconi, G., 2004. Durable fiber reinforced self-compacting concrete. Cem. Concr. Res. 34, 249–254.
Dehn, Frank, Leipzig Germany, Private communication with Naaman, A.E., 2005.
Dinakar, P., Babu, K.G., Santhanam, M., 2008. Durability properties of high volume fly ash self compacting concretes. Cem. Concr. Compos. 30, 880–886.
Gesoglu, M., Guneyisi, E., Ozbay, E., 2009. Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silicafume. Constr. Build. Mater. 23, 1847–1854.
Gibs, J.C., Zhu, W., (1998). Strength of hardened self compacting concrete. Brite Euram Project No. BE96-3801/Contract BR/PR-CT 96-0366, Non-confidential information, pp. 199–209.
Groth, P., Nemegeer, D., 1999. The use of steel fibres in self-compacting concrete. In: Skarendahl, A., Petersson, O. (Eds.), Proceedings of the First International RILEM Symposium on Self Compacting Concrete. Stockholm, Sweden: 13–14 September 1999, pp. 497–507.
Grünewald, Steffen, Walraven, Joost C., (2001). Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-consolidating concrete, 2001.
Gutha, S., 2010. Comparative Study of Properties of Different Types of Binder Mixes Modified with Silica Fume. Department of Civil Engineering, National Institute of Technology, Rourkela.

IS 9103-1999, Concrete Admixtures-specification" Bureau of Indian Standards, Manak Bhavan, 9 Bahadur Shahzafarmarg, New Delhi-110002.
Johnston, C.D., 2001. Fiber-Reinforced Cements and Concretes. Gordon and Breach Science Publishers, Amsterdam.
Khayat, K.H., Roussel, Y., 1999. Testing and performance of fiber-reinforced, self-consolidating concrete. In: Skarendahl, A., Petersson, O. (Eds.), Proceedings of the First International RILEM Symposium on Self Compacting Concrete. Stockholm, Sweden: 13-14 September 1999, pp. 509–521.
Massicotte, Bruno, Degrange, Gerard, Dzeletovic, Nikola, 2000. Mix design for SFRC bridge deck construction. In: RELIM PRO15 Fiber-Reinforced Concretes BEFIB, pp. 119–128.
Okamura, H., Ouchi, M., 1999. Self-compacting concrete. Development, present use, and future. In: Proceedings of the First International RILEM Symposium on Self-Compacting Concrete, Stockholm, Sweden, pp. 3–14.
Ransinchung R.N., G.D., Kumar, Brind, Kumar, Veerendra, nsinchung et al. 2009. Assessment of water absorption and chloride ion penetration of pavement qualtity concrete admixed with wollastonite and microsilica. Constr. Build. Mater., Elsevier 23, 1168–1177.
Sahmaran, Mustafa, Yaman, I. Ozgur, 2007. Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash. Constr. Build. Mater. 21 (1), 150–156.
Sahmaran, Mustafa, Yurtseven, Alperen, Yaman, I. Ozgur, 2005. Workability of hybrid fiber reinforced self compacting concrete. Build. Environ. 40, 1672–1677.
Suter, R., Butschi, P.Y., (2001). "Tunnel du Oenzberg/Voussoirs en Beton, avec ou sans fibres," in French, Mandat de Recherche No. P.0209, EIA-Fribourg, Switzerland.
Tanaka, K., Sato, K., Watanabe, S., Arima, I., Suenaga, K., 1993. Development and utilization of high performance concrete for the construction of the Akashi Kaikyo Bridge. In: Zia, P. (Ed.), SP-140: High Performance Concrete in Severe Environments. American Concrete Institute, Detroit, MI, pp. 147–161.
The European Project Group, 2005. The European Guidelines for Self-compacting Concrete. SCC European Project Group.

Further Reading

Technical Bulletin TB – 1500, GRACE Construction Products. "An Introduction to Self Compacting Concrete (SCC)".
Lange, David A., Struble, Leslie J., Dambrosia, Matthew D., Shen, Lin, Tejeda-Dominguez, Fernando, Birch, Benjamin F., Brinks, Andrew J., 2008. Performance and Acceptance of Selfconsolidating Concrete, Research Report FHWA-ICT-08-020. Illinois Center for Transportation.