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Development of Fiber Reinforced SCM for Sustainable Construction

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Abstract

The sustainability of the built environment is increasingly coming to the forefront of infrastructure design and maintenance decisions. To address this, development of a new class of more sustainable cement-based materials is needed. Fiber reinforced self-consolidating mortar (FRSCM) was developed by optimizing the micromechanical parameters, which control composite properties in the hardened state, and the processing parameters, which control the rheological properties in the fresh state. The addition of fibers may take advantage of its high performance in the fresh state to achieve a more uniform dispersion of fibers, which can help to mitigate the shrinkage of the self-consolidating composite. In other words, fibers can have rheological and mechanical synergistic effects and that optimized fiber combinations can better increase mechanical performance while maintaining adequate flow properties for fiber reinforced self-consolidating mortar. In this study, effects of aspect ratio (l/d) and volume fraction (V_f) of polypropylene (PP) fiber on the free shrinkage and mechanical properties of FRSCM were investigated. Besides, the rheological properties of fiber reinforced SCMs are investigated by mini-slump and mini V-funnel tests. Nine mortar mixtures are prepared containing 0 to 0.7 percent of 6 and 12 mm length polypropylene fibers. The shrinkages of hardened mortar were measured since removing the molds and the measurements were continued up to six months. The results show that, the optimum volume fraction of polypropylene fiber content in SCMs to achieve appropriate rheological and mechanical properties is about 0.3% of the mixture volume. On the other hand, increasing the volume fraction and aspect ratio of PP fibers to about 0.7% causes the mechanical properties to drop considerably. This could be due to balling of fibers or fibers coagulation in the mixtures which decreases the mechanical properties.
Keywords: Self-consolidating mortar; Polypropylene fiber; Shrinkage; Mechanical properties; Rheological properties

1. Introduction

Self-consolidating concretes (SCCs) turn out to be materials for the realization of building structures and components, with more durability than the standard concretes. The greater durability of self- consolidating concretes satisfies the request for sustainability, because it will be possible to delay the maintenance and, therefore, limit the volumes of deteriorated concrete to be disposed of and lower use of repair mortars based on special mixtures big consumers of non-renewable resources. Nowadays, the use of highly-flowable or self-consolidating cement based mixtures is common in building industries. This is due to high workability and elimination of vibration in these composites. The self-consolidating trait of these composites helps in placing by their own weight. Due to higher volume of paste in these mixtures than ordinary mixtures, the cracking susceptibility of them are often raised [1]. The increase in the volume of paste improves the workability but it may decrease the mechanical and time-dependent deformations properties. Cementitious materials are typically characterized as brittle, with a low tensile strength and strain capacity. On the other hand, the drying shrinkage and non-restrained shrinkage increases with an increase in volume of paste [2,3]. Thus, shrinkage of the cement based mixtures is mostly related to the cement paste content in them. Fibers have long been used in cement-based materials to obtain enhanced material performance. Substantial increase in tensile strength and toughness is the most acknowledged feature of fiber-reinforced composites [4]. Some other benefits gained using fibers include increased shear strength and increased resistance

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to dynamic loads [5,6,7]. Randomly distributed fibers provide bridging forces across cracks and thus prevent them from growing. This effect strongly depends on the aspect ratio r of the fiber, namely the ratio between the length L and the diameter d of the fiber and on the concentration of fibers.

By the process of curing and drying of the mixture, tensile stresses occur due to hydration and loss of moisture. The tensile stresses result in surface cracking of the mixture. If these cracks that develop as a result of shrinkage remain unnoticed, they become channels for passage of external deteriorating agents and reduce long-term durability [8].

Four main types of shrinkage are cited in the literature. The shrinkage of hardened concrete due to drying is referred to as drying shrinkage, while plastic shrinkage is used to describe the shrinkage of fresh concrete due to early age moisture loss from the concrete before, or shortly after, the concrete sets. Carbonation shrinkage is caused by the chemical reaction of various cement hydration products with carbon dioxide in the air. Carbonation shrinkage is limited to the surface of the low-permeable concrete [9]. Autogenous shrinkage, which occurs when a concrete can self-desiccate during hydration, and which becomes more significant as the strength of concrete is increased, is analogous to drying shrinkage [10]. One highly effective technique of controlling plastic shrinkage cracking is reinforcing concrete with fibers. Randomly distributed fibers of steel, polypropylene, etc. provide bridging forces across cracks and thus prevent them from growing [11,12]. The addition of non-metallic fibers such as polypropylene, glass, polyethylene, etc. is reported to reduce drying shrinkage crack widths of concrete at later ages [13]. Of all fibers currently used for the purpose of controlling the shrinkage cracks, polypropylene is considered to be the most effective. Polypropylene is inexpensive, inert in high pH cementitious environment and easy to disperse. However, the exact influence of polypropylene fiber geometry, diameter, length, fibrillations, etc. is not well understood [14].

The mechanism of controlling shrinkage by fibers is known to be by gradually discharging absorbed water of mixture in fibers and compensating the drop in pore water level due to hydration and loss of moisture which causes increase in pore water pressure which tends to bring neighboring particles closer [15].

With an increase in the non-metallic fiber content, even though the crack characteristics are significantly improved, the concrete mixtures lose their workability [15], thus the difficulty of casting increases. This situation mostly results in inadequate workability and high volumes of entrapped air in concrete, which causes strength loss and reduces the service life of material.

Fibres can have rheological and mechanical synergistic effects and that optimised fibre combinations can better increase mechanical performance while maintaining adequate flow properties for fibre-reinforced self-compacting cementitious composites [16-18].

In this paper, the results of an investigation on the shrinkages and mechanical properties of a self-consolidating (highly flowable) mortar reinforced with polypropylene (PP) fiber are presented. There is some evidence that proves SCM could be categorized as a kind of SCC. Therefore, the rheological properties of SCC can be obtained by generalizing the test results done on SCM mixtures, due to similarities between their mixtures, especially in the amount of fine aggregates. Besides, the test results on SCM are achieved faster than SCC. Thus, nine mortar mixtures are prepared containing 0, 0.1, 0.3, 0.5 and 0.7 percent of 6 and 12 mm length PP fibers. The effect of fiber length and fiber content on total shrinkage of the cementitious material is investigated in this research using shrinkage curves over 180 days. The rheological properties of fresh SCMs are investigated by mini-slump and mini V-funnel flow time test. Besides, the effects of fiber content and fiber length on mechanical properties of hardened concrete are considered; and the 28 days compressive, splitting tensile and flexural strengths of the mixtures are determined.

2. Experimental program

2.1. Characterization of materials

ASTM C 150 Type I Ordinary Portland Cement (OPC) was used for all the mixtures. The chemical composition and physical properties are presented in Table 1. Well-graded sand based on ASTM C33, with a fineness modulus of 2.76, specific gravity of 2.7, absorption value of 2.8% and maximum aggregate size of 1.18mm, was employed in all mixtures. The aggregate size distributions are shown in Figure 1.

A polycarboxylic-based superplasticizer (SP) was used. Its solid content and specific density are 36% and 1.07, respectively. Commercial polypropylene fibers in the form of collated fibrillated fiber bundles of 6 and12 mm length were also employed. Polypropylene fibers are highly hydrophobic with a very smooth surface structure. Properties of the PP fibers are presented in Table 2.

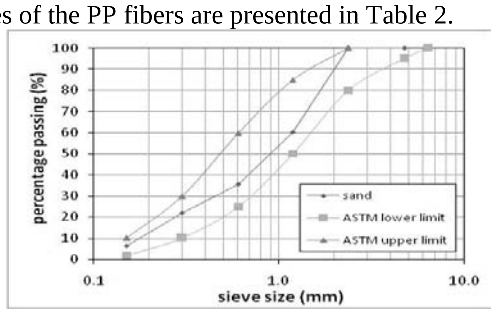


Fig. 1. Sand size distribution

Table 1. Chemical analysis and physical properties of cement

properties	%
Chemical	
Insoluble residue	0.38
SiO_2	20.03
Al_2O_3	5.53
Fe_2O_3	3.63
CaO	62.25
MgO	3.42
SO_3	2.23
Na_2O	0.3
K_2O	0.73
Ignition Loss	1.37
Physical	
Specific Gravity	3.15
Blain Fineness(m^2/kg)	300
Initial setting time (min)	188
Final setting time (min)	240

Table 2. Properties of PP fiber

Length (mm)	Geometry	Density (Kg/m^3)	Diameter (mm)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Aspect Ratio (*r*) l/d
6	Fibrillated	910	0.02	400	3450	300
12	Fibrillated	910	0.02	400	3450	600

2.2. Mixture Properties

The performance of SCMs incorporating PP fibers is investigated through the following experiments. At the beginning, the optimum admixture dosage and maximum possible fiber content are determined. Then, the mechanical performances of SCMs reinforced by the maximum possible amount of fibers (in 2 sizes) are compared. In all mixtures water-cement ratios are 0.4, and aggregate content is kept constant at 1170 kg/m^3. The cement content is fixed at 700 kg/m^3, and the SP content is 1% of cement mass. By keeping mixture variables constant and varying only the fiber parameters, the goal was to isolate the individual effects of fiber synergy. Table 3 presents the composition and labeling of the SCMs prepared with PP fibers.

Table3. Mix proportions

Label	Size of polypropylene fiber	Fiber content	
	mm	%	kg/m^3
CM*	-	0	0
SP1	6	0.1	0.9
SP2	6	0.3	2.7
SP3	6	0.5	4.5
SP4	6	0.7	6.3
LP1	12	0.1	0.9
LP2	12	0.3	2.7
LP3	12	0.5	4.5
LP4	12	0.7	6.3

*Control mixture

2.3. Test Methods

All specimens were fabricated according to ASTM C 192/C 192M-02, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

2.3.1. Mini Slump Test

The mini-slump test is based on the measurement of the spread of mortar placed into a cone-shaped mould. The truncated cone (diameters: 100 and 70mm, height: 60mm) is placed on a smooth and non-absorbing plate, filled with paste and lifted. The resulting final diameter of the fresh paste sample is the mean value of two measurements made in two perpendicular directions as shown in Figure 2.

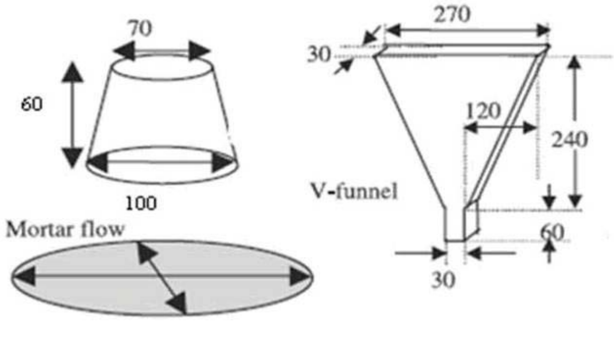


Fig. 2. Dimensions of mini-slump and mini V-funnel

2.3.2. Mini V-funnel Test

This test consists of measuring the time required for a given volume of mortar (1 liter) to flow through the nozzle. This test is often used to measure the viscosity of the mortar which may be related to properties such as cohesiveness, pumpability and finishability. It should be noted that due to instability or inadequate flowability of mortars, the V-funnel values of some mixtures could not be measured. The instrument used in this test is shown in Figure 2.

2.3.3. Shrinkage measurement

After fabricating the shrinkage specimens, they were covered with wet burlap. The plastic sheet was not used for covering the specimens because there was no concern about keeping the burlap wet in the first 24 hours. After 24 hours of wet curing, the specimens were removed from the steel molds. The test method involves measuring the length change of 75mm×75mm×285mm specimens using a length comparator shown in Figure 3 in accordance with C 490-00a, Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete. When initial readings were taken, the specimens were placed freely on a table and covered with a plastic sheet for keeping the temperature and humidity in a relative range. The length change measurements were conducted in the 1st, 2nd, 3rd, 5th and the 7th day of the first week. Subsequent length change measurements were conducted every week up to 28 days, and then every month up to 180 days.

Fig. 3. Measurement of shrinkage strain

3. Results and discussion

3.1. Rheology of Fresh SCMs

Fibers can affect rheology of concrete and the optimized fiber combinations can better increase mechanical performance while maintaining adequate flow properties for fiber reinforced SCM. Additionally, the test results reported by En-Hua Yang et al. indicated that the good correlations between relative yield stress and mini-slump flow deformation, and between plastic viscosity and mini V-funnel flow time [19,20]. Therefore, the rheological properties of SCM mortar can be effectively evaluated by the easier mini-slump and V-funnel test in the field for quality control purposes. Therefore, in this research, mini-slump and mini V-funnel tests were conducted as the rheological tests.

3.1.1. Fluidity

The results of mini-slump flow test are presented in Figure 4. As expected, the control mixture achieved one of the highest slump flow values. As polypropylene fibers were added, mini-slump values generally became lower.

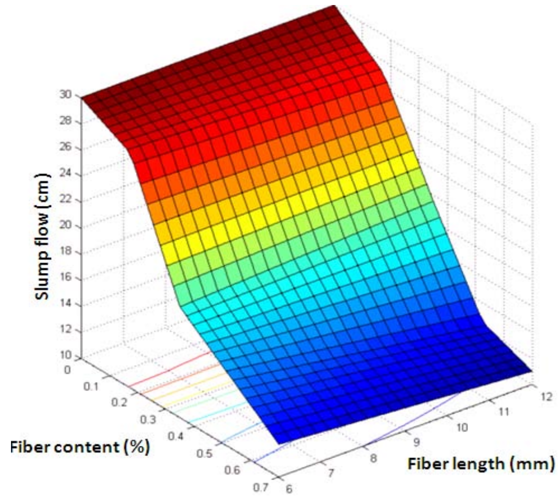


Fig. 4. Result of mini-slump test

The relative fluidity results (i.e. ratio between the fluidity of the mixtures containing fibers and the fluidity of the control mixture) of mini-slump flow test are presented in Figure 5. Linear regression analysis of the mini-slump results shows that in constant W/C ratio, increasing volume fraction by about 0.7% for fibers with 6 mm and 12 mm length decreased the slump flow by about 60% and 65% respectively. Furthermore, doubling the length of fibers, with the same fiber content ratio does not have significant effect on the fluidity of the mixtures.

Bleeding is also measured in the mini-slump flow test. Bleeding of the mixtures is summarized in Figure 6. This figure clearly shows that by using the PP fibers at low volume fraction (less than 0.3%) bleeding of the mixtures was completely controlled In contrast, much more visible bleeding can be observed at high volume fraction of SCM specimens. This could be due to balling of fibers or fibers coagulation in the mixtures. As can be seen in Figure 7, when high volumes of long PP fibers were incorporated in SCM, the fibers tended to become entangled together and formed clusters at the center of the flow spread. This agrees with results of Grunewald and Walraven who noted that self-compacting concrete can be achieved when polymer fibers are used, but the total fiber volume must be less than approximately 0.4%. Therefore, using short fiber and limited fiber volume fraction are necessary to ensure uniform fiber dispersion and to minimize the reduction in matrix deformability [21].

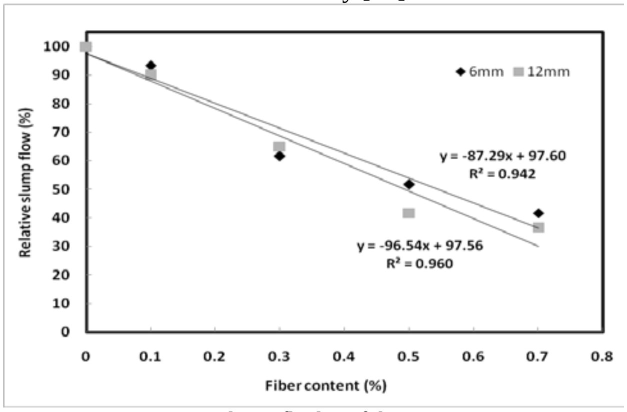


Fig. 5. Relative fluidity of the mixtures

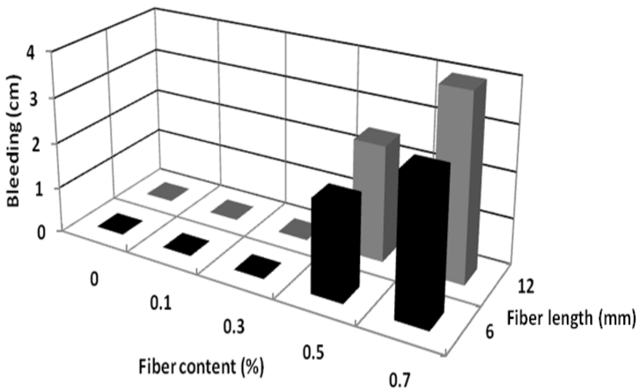


Fig. 6. Bleeding of the mixtures

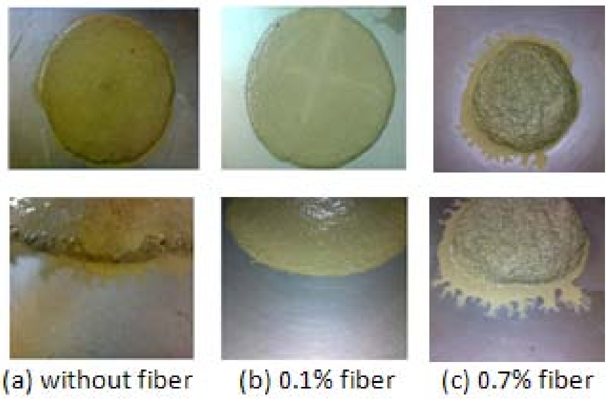


Fig. 7. Consistency of a mortar mixed with PP fiber with various fiber dosages

3.1.1. Viscosity

Figure 8 presents the results of flow time results. As expected, PP fibers can increase the viscosity of SCM as the fiber volume fraction and aspect ratio (length/diameter) increase. Blockage of the aggregates is evaluated indirectly in the mini V-funnel test. Blockage region of the mixtures is presented in Fig. 8. As shown in the figure, mixtures with higher fiber content are prone to aggregate blockage while flowing narrow section of mini V-funnel nozzle. This is due to balling of fibers, as it was mentioned before. This means that self-compactibility cannot be maintained. In self-consolidating concrete (SCC), viscosity is a dominant factor to prevent segregation caused by inhomogeneous flow between the ingredients of the fresh mixture and gravitational sedimentation.

It can therefore be concluded that, the rheological properties of fresh fiber reinforced SCM mix are also strongly affected by the fiber dispersion in the matrix. Poor fiber dispersion may decrease the flowability of matrix significantly. Therefore, the original flow properties of matrix mix can be greatly reduced. Further hampering of the flow properties are the potential entanglement. In order to make fiber reinforced SCM, the above negative effects should be minimized, so that the deformability of fresh matrix can be preserved as much as possible. Therefore, using short fiber and limited fiber volume fraction are necessary to ensure uniform fiber dispersion and to minimize the reduction in matrix deformability. Based on our experiments, the minimum acceptable spread of slump test is about 20 cm. Figures 4 and 8 show that, the optimum fiber content ratio for maintaining workability of the mortar with appropriate flowability and viscosity is about 0.3% for both fiber lengths.

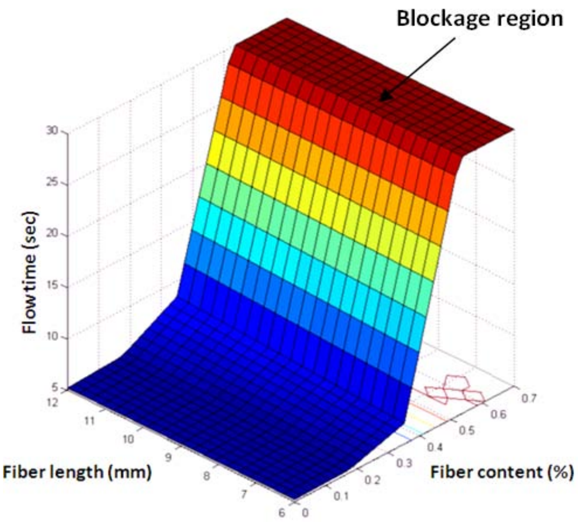
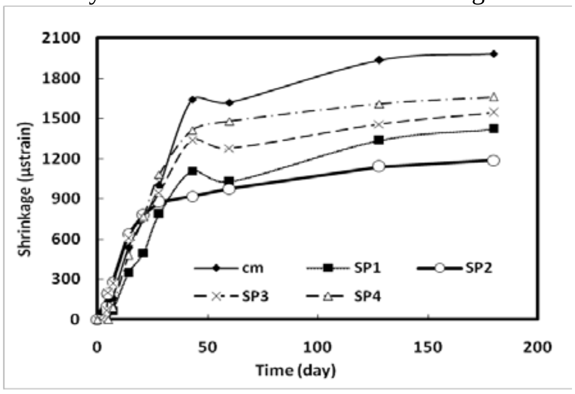


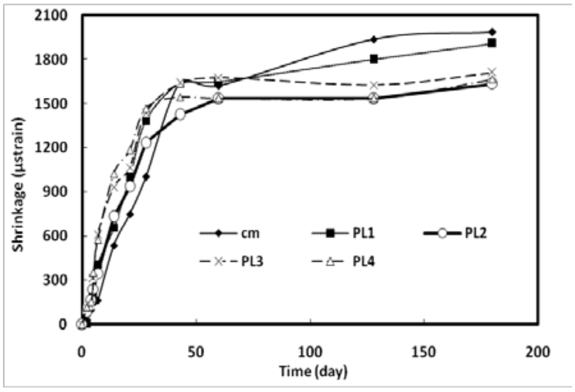
Fig. 8. Result of flow time test

3.2. Non-restrained shrinkage of hardened mortar

High flowability of SCMs causes fibers to uniformly disperse in the mixture. The use of fibers in such composites can lead to lower shrinkage strains. In this study, shrinkage of the specimens was measured up to 180 days. The shrinkage curves are presented in Figures 9a and 9b. It's clear that with constant water-cement ratio the addition of PP fibers of both sizes decreases the shrinkage strains of the mortar. But increasing the amount of fiber content does not necessarily lead to lower shrinkage strains. By considering this conclusion and reviewing the results presented in previous section, 0.3% of fiber content is the most appropriate amount of fiber in a SCM mixture, in the sense of achieving a good flowability and the best control of the shrinkage.



(a) 6mm PP fiber



(b) 12mm PP fiber

Fig. 9. Shrinkage curves of PP fiber reinforced SCMs

Figure 10, representing comparative information about shrinkage strains of mortar specimens reinforced with 6mm and 12mm PP fibers, indicates that 6mm fibers have greater ability in controlling the shrinkage of specimens. By the same volumetric fiber content, the number of 6mm fibers is two times greater than 12mm fibers. So the former can be much more distributed in the mixture. This means that 6mm fibers can spread the discharged water better than 12mm fibers. Consequently the drop in pore water level can be better compensated. Thus the shrinkage of mortars reinforced with 6mm fibers are less than those reinforced with 12mm fibers.

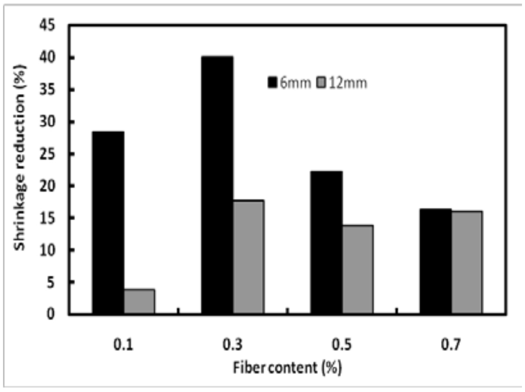


Fig. 10. Effect of PP fibers on shrinkage reduction after 180 days

3.3. Hardened properties of fiber reinforced SCMs

Results of compressive strength for all mixtures are presented in Figure 11. Fibers seem to have no significant effect on compressive strength of mortars. On the other hand, excessive fibers decrease the sample strength. In this research, the compressive 28 days strength of samples made with 0.1% and 0.3% of both fiber sizes show trifle difference from the control sample. Increasing the length and amount of fibers to about 0.7% causes the compressive strength to drop considerably, as it is shown in Figure 11. This could be due to the fact that sample compaction and homogeneity are influential in the final strength of the samples. Soroushian, Khan, and Tsu also observed that compressive strength was reduced due to the addition of polymer fibers[22].

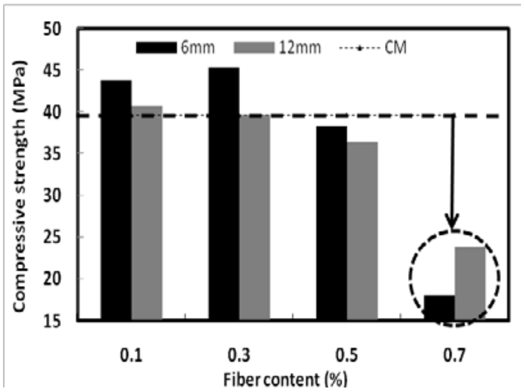


Fig. 11. Compressive strength of PP fiber reinforced SCM

The results of splitting tensile strength (STS) tests for fiber reinforced SCM mixtures are summarized in Figure 12. As Figure 12 illustrates, splitting tensile strength indicated significant increase in strength due to the inclusion of PP fibers. The obtained results show that splitting tensile strength of control mixture is obtained as 2.46 MPa. For 6 mm length of fiber of (SP1-SP8), and 12 mm (LP1-LP8) the minimum and maximum split tensile strength values are 4, 4.2 MPa and 2.37, 2.3 MPa, respectively. As observed in this investigation, the split tensile strength increases with the increase in aspect ratio of the fibers in the cement paste mix, hence the longer fibers are offering more resistance to the pull out of fibers out of the cement paste matrix because of their better bond characteristics being longer in length. On the other hand, increasing the length and amount of PP fibers to about 0.7% causes the STS to drop considerably, as it is shown in Figure 12. This could be due to balling of fibers or fibers coagulation in the mixtures which decreases the mechanical properties.

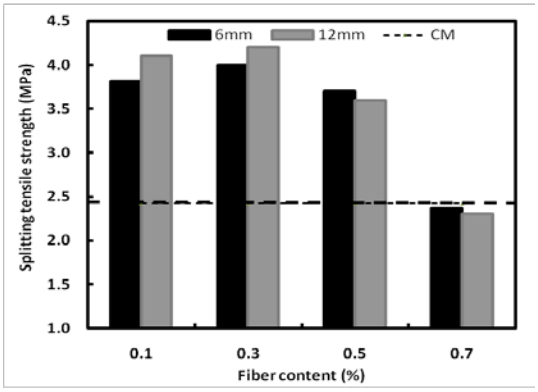


Fig. 12. Splitting tensile strength of PP fibers reinforced SCM

Results of flexural strength for all mixtures are presented in Figure 13. The results of flexural strength tests for the mixtures indicate a beneficial contribution of polypropylene fibers to the prepeak behavior of fiber reinforced SCM. This is expected because it is known that microfibers bridge microcracks, which delays the development of macrocracks. Flexural strength of control concrete was 3.5 MPa. For 6mm length of fiber of (SP1-SP8) and 12mm (LP1-LP8) the minimum and maximum flexural strength values are 4.5, 4 MPa and 6.6, 6.9 MPa, respectively. On the other side, the mixture incorporating the highest fiber factor (LP8) had the lowest flexural strength. This weak interface bonding can potentially generate lower fiber bridging stress that can result in low flexural strength.

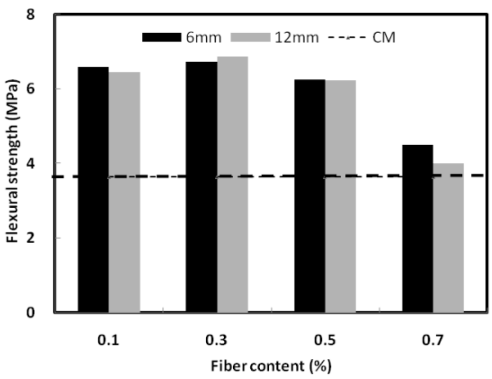


Fig. 13. Flexural strength of PP fibers reinforced SCM

4. Conclusions

This investigation compiles rheological and mechanical test results with experimental shrinkage strain curves obtained from specimens of fiber reinforced self-consolidating mortar (SCM) fabricated by two sizes of polypropylene fibers. The main conclusions of the study are as follows:

1. In constant water-cement ratio, increasing the aspect ratio and volume fraction of polypropylene fibers causes rheological properties such as viscosity and yield stress to increase considerably.
2. A direct relationship between stability of the mortar and ability of fiber content in controlling the shrinkage strains can be recognized. Thus, considering the effect of fiber content on the stability of mortar, using more fiber does not necessarily result in lower shrinkage strains.
3. The dispersion of 6mm length polypropylene fibers is considerably better than those of 12mm length PP fibers. So these fibers can discharge the absorbed water more effectively. This leads to higher ability in controlling shrinkage in large specimens.
4. There seems to be a certain limit of fiber content, beyond which the reduction in shrinkage continues with a lower rate.
5. Increasing the length and amount of PP fibers to about 0.7% causes the mechanical properties to drop considerably. This could be due to balling of fibers or fibers coagulation in the mixtures which decreases the mechanical properties.
6. Fibers can have rheological and mechanical synergistic effects and that optimized fiber combinations can better increase mechanical performance while maintaining adequate flow properties for fiber reinforced self-compacting mortar. The results show that, the optimum volume fraction of polypropylene fiber content in SCMs to achieve appropriate rheological and mechanical properties is about 0.3% of the mixture volume.

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