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Combined effect of silica fume and polypropylene fiber on drying shrinkage properties of concrete composites containing fly ash

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Workability;
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Fly ash;
Silica fume;
Polypropylene fiber.

Abstract. A parametric experimental study has been conducted to investigate the combined effect of silica fume and polypropylene fiber on the workability and drying shrinkage of concrete composite containing fly ash. Four contents of fly ash, four silica fume contents and four different fiber volume fractions were used. The results indicate that fly ash can not only improve the workability but also lower the drying shrinkage of the concrete composite. The workability of the concrete composite becomes better and better and the drying shrinkage strain is decreasing gradually with the increase of fly ash content. Besides, silica fume has adverse effect on both of the workability and drying shrinkage property of concrete composite containing fly ash. With the increase of silica fume content, both the slump and slump flow of the concrete containing fly ash decrease gradually, while the drying shrinkage strain has an increasing tendency. In addition, polypropylene fiber can greatly restrict the drying shrinkage of concrete composite containing fly ash and silica fume, and there is a tendency of decrease in the drying shrinkage strain with the increase of fiber volume fraction. However, polypropylene fiber has a little adverse effect on the workability of concrete composite.

1. Introduction

Today, as a common mineral admixture, fly ash is often used in order to improve some mechanical and physical properties of concrete, and to reduce its cost [1-4]. Fly ash is obtained as a waste product during the combustion of pulverized coal in thermal power plants. Fly ash is used as an admixture in cement and concrete because of its pozzolanic and/or self-cementitious nature [5]. Besides, as is known, concrete industry, especially Portland cement manufacture is a heavy contributor to the environmental damage and CO_2 emissions. Using fly ash as a cement replacement could result in a substantial contribution to reduce the overall CO_2 emissions of the final concrete product [6]. However, concretes containing fly ash tend to have slower strength development, especially at high cement replacement rates, since the Portland cement reaction (hydraulic) is much faster than the fly ash reaction (primarily pozzolanic) [7,8]. The pozzolanic reaction can only take place if there is available calcium hydroxide, a by-product of the hydraulic reaction. Therefore, the contribution of fly ash towards the strength development occurs only at later ages [9].

Silica fume, also known as micro-silica, is a byproduct of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys [10]. Silica fume is an amor-

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phous mineral material composed of extremely small, chemically active particles of SiO_2 that appear as a by-product in silicon or ferrosilicon industries. It can be considered a supplementary cementing material that improves the mixture particle packing and the compactness of the concrete. Its great specific surface area results in a high chemical activity with the calcium hydroxide released as a consequence of cement hydration (pozzolanic activity), which is considered responsible for the significant increase of the early compressive strength of the silica fume added to concrete [11,12]. Therefore, to increase the early strength of concrete containing fly ash, the application of silica fume together with fly ash provides an interesting alternative, and many researchers have recently conducted investigations, using a combination of the two by-products [13,14]. However, the concrete structures will become brittle after the concrete mixture is added into silica fume [15]. Besides, the concrete is more prone to early age cracking caused by shrinkage, due to the use of mineral admixtures such as silica fume [16]. Polypropylene fiber is a kind of man-made synthetic fiber with the properties of low modulus of elasticity, high strength, excellent ductility, excellent durability and low price, so it is used widely in cement-based materials to improve the toughness and anti-cracking performance of the matrix [17-21].

Early age cracking of concrete results from the interplay between the volume instability, mechanical properties of concrete and different types and degrees of restraint [22]. When the concrete behaves like a fluid, i.e. during the very early age, its volumetric changes are usually not of a great concern in terms of stress generation, because the concrete deforms plastically without generating stresses. However, once it has transformed a visco-elastic solid, the stress is generated [16,23]. The drying shrinkage property of concrete is so important in the mix design and application of concrete, especially when the concrete is used in drying environment. However, so far, there is little report about the shrinkage property of fly ash concrete composites containing silica fume and polypropylene fiber. Studying the shrinkage property is certainly necessary and helpful to promote the application of the new concrete material. This article reports the investigation of the combined effect of silica fume and polypropylene fiber on shrinkage properties of the concrete containing fly ash.

2. Experimental program

2.1. Raw materials

Ordinary Portland cement (Class 42.5R) produced by Tongli Factory, Grade I fly ash and silica fume were used in this work. The cement, fly ash and silica fume properties are given in Table 1. The polypropylene fiber used in this investigation was bunchy single short fiber, which was produced by Danyang Synthetic Fiber Plant in the Jiangsu Province of China. The basic physical properties of polypropylene fiber in this study are shown in Table 2. Coarse aggregate with a maximum size of 20 mm and fine aggregate with a 2.82 fineness modulus were used in this experiment. A high range water reducer agent with a commercial name of polycarboxylate HJSX-A was used to adjust the workability of the concrete mixture. Fly ash and silica fume were mixed in concrete composites by replacing the same quantity of cement, and polypropylene fiber was mixed in concrete with the dosage of cementitious materials unchanged. Fly ash content (by mass) is from 10% to 25% and silica fume content (by mass) is from 3% to 12%, and the dosage (by volume) of polypropylene fiber is from 0.06% to 0.12%. Mix proportions are given in Table 3.

Table 1. Properties of cement, fly ash and silica fume.

Composition (%)	**Cement**	**Fly ash**	**Silica fume**
Chemical compositions			
SiO_2	20.17	51.50	93.72
Al_2O_3	5.58	18.46	0.82
Fe_2O_3	2.86	6.71	0.48
CaO	63.51	8.58	0.34
MgO	3.15	3.93	1.44
Na_2O	0.12	2.52	0.40
K_2O	0.57	1.85	1.22
SO_3	2.56	0.21	0.47
Physical properties			
Specific gravity	3.05	2.16	2.30
Blaine fineness (m^2/kg)	329.5	247	-

2.2. Preparation of fresh concrete composite

In order to distribute silica fume and the fibers uniformly, a forced mixing machine was adopted. Fibers were dispersed by hand in the mixture to achieve a uniform distribution throughout the mixture. The mixing procedure, which was designed by trial and error, was chosen as follows: the coarse aggregate and fine aggregate were mixed initially for 1 min, and the binder and polypropylene fiber were mixed for another 1 min. Finally, the high range water reducer agent and water were added and mixed for 3 min. The distribution of silica fume and the fibers has great effect on the working performance of the mixture and the water impermeability of the concrete composite. If silica fume and the fibers are not distributed well, they will be assembled altogether. From the working performance of the mixture, and the fracture section of the specimen of the concrete composite reinforced with

Table 2. Physical properties of polypropylene fiber.

Density (g/cm^3)	Linear density (*dtex*)	Fiber length (mm)	Tensile strength (MPa)	Elastic modulus (MPa)	Melting point (°C)
0.91	10-20	10-20	≥ 450	≥ 4100	160-170

Table 3. Mix proportions of the concrete mixtures.

Mix no.	Cement (kg/m^3)	Fly ash (%)	Fly ash (kg/m^3)	Silica fume (%)	Silica fume (kg/m^3)	Fiber volume fraction (%)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Water reducer agent (kg/m^3)
1	494.0	-	-	-	-	-	647	1151	158	4.94
2	444.6	10	49.4	-	-	-	647	1151	158	4.94
3	419.9	15	74.1	-	-	-	647	1151	158	4.94
4	395.2	20	98.8	-	-	-	647	1151	158	4.94
5	370.5	25	123.5	-	-	-	647	1151	158	4.94
6	405.1	15	74.1	3	14.8	-	647	1151	158	4.94
7	390.3	15	74.1	6	29.6	-	647	1151	158	4.94
8	375.4	15	74.1	9	44.5	-	647	1151	158	4.94
9	360.6	15	74.1	12	59.3	-	647	1151	158	4.94
10	390.3	15	74.1	6	29.6	0.06	647	1151	158	4.94
11	390.3	15	74.1	6	29.6	0.08	647	1151	158	4.94
12	390.3	15	74.1	6	29.6	0.10	647	1151	158	4.94
13	390.3	15	74.1	6	29.6	0.12	647	1151	158	4.94

polypropylene fiber, it can be seen that silica fume and the fibers of this study have been distributed well.

2.3. Workability test

The workability of the fresh concrete composites can be evaluated by the parameters of slump and slump flow. The slump flow can be expressed as the spreading diameter of the fresh concrete composite in the slump test. The slump can reflect the fluidity of the fresh concrete composite, and the slump flow can reflect the cohesive properties of the fresh concrete composite. From the spreading process in the slump test, the segregation-resistance ability of the fresh concrete composite can be assessed. The values of slump and slump flow can be measured using a standard slump cone made of thin steel sheet of which the height, the diameter of upper open mouth and the diameter of the bottom are 300 mm, 100 mm and 200 mm, respectively. The slump cone should be placed on a smooth and flat plate before the fresh concrete composite was put into the slump cone in three layers, and each layer was tamped for 25 times by a tamping bar. The excessive fresh concrete composite should be scraped off with a trowel. After the slump cone was lifted vertically, it should be placed on the flat plate alongside the fresh concrete composite slumped from the slump cone. The difference of the maximum height of the fresh concrete composite and the height of the slump cone was measured as the value of slump. The final maximum and minimum diameters of the spreading fresh concrete composite were measured to calculate the value of slump flow. If the difference of the maximum and minimum diameters is less than 50 mm, the average of the two diameters can be taken as the value of slump flow. The larger values of slump and slump flow indicate that the fresh concrete composite has better workability.

2.4. Drying shrinkage test

The tests of drying shrinkage properties of concrete composite were carried out in accordance with the Chinese Standard [24]. A series of beam specimens with the size of $100 \times 100 \times 400$ mm^3 were used to determine the shrinkage properties of the concrete composite. For the shrinkage properties of concrete composite test, each set of mix includes 6 specimens, and the average value of the 6 data was computed as the final result. After the specimens were cast, the moulds had to be removed the next day, and the specimens were put into the standard and curing room to be cured at 100% relative humidity and controlled temperature (20 ± 2°C). After the specimens were cured for two days, the initial lengths of the specimens had to be measured, and then they were put into the shrinkage room to be further cured at 60 ± 5% relative humidity and controlled temperature (20 ± 2°C). There are 10 curing periods, and the length variation of the specimen should be measured by the dial indicator at the end of each period to calculate the drying shrinkage strain. The testing apparatus of drying shrinkage is presented in Figure 1.

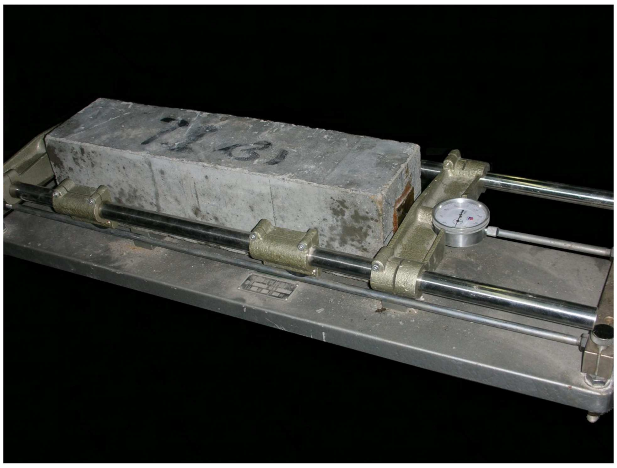

Figure 1. Testing apparatus of drying shrinkage.

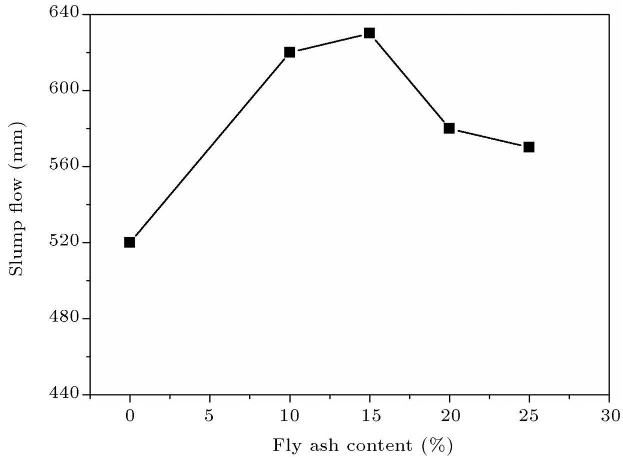

Figure 3. Effect of fly ash content on slump flow.

3. Results and Discussion

3.1. Slump and slump flow

3.1.1. Effect of fly ash content on slump and slump flow

The variations of the slump and slump flow of concrete composite containing fly ash versus fly ash content are illustrated in Figures 2 and 3, respectively. The slump and slump flow are increasing gradually with the increase of fly ash content when the fly ash content is not beyond 15%. Compared with the concrete without fly ash, the increase of the slump and slump flow were determined as 25% and 21.2% for the concrete composite with 15% fly ash content, respectively. After the content of fly ash increases continuously from 15% to 25%, both the slump and slump flow become lower gradually, however, the values of the slump and slump flow are still higher than that of the concrete without fly ash. Because fly ash is composed of a great quantity of ball glass beads, the addition of fly ash in concrete has a great morphology effect, which can also be called lubrication action [25]. This lubrication action stops the cement particles from sticking together. Besides, approximately spherical fly ash particles provide ball bearing effects and reduce internal friction in fresh concrete, and thus increase the flow ability and compaction of the concrete [26,27]. Therefore, the addition of fly ash can improve the workability of concrete. However, when the fly ash content is more than 15%, the total specific surface area of the fine particles becomes larger, and the water demand becomes larger, which increases the cohesiveness of the concrete mixture. Therefore, the workability of concrete begins to decrease. The variations indicate that the small content of fly ash can improve the workability of concrete composite, while the overlarge fly ash content may be adverse to the workability of concrete composite.

3.1.2. Effect of silica fume content on slump and slump flow

Figures 4 and 5 present the varying rules of the slump and slump flow of concrete composite with 15% fly ash with the increase of silica fume content, respectively. As can be seen from the figures, in general, the addition of silica fume can decrease the slump and slump flow of the concrete composite with

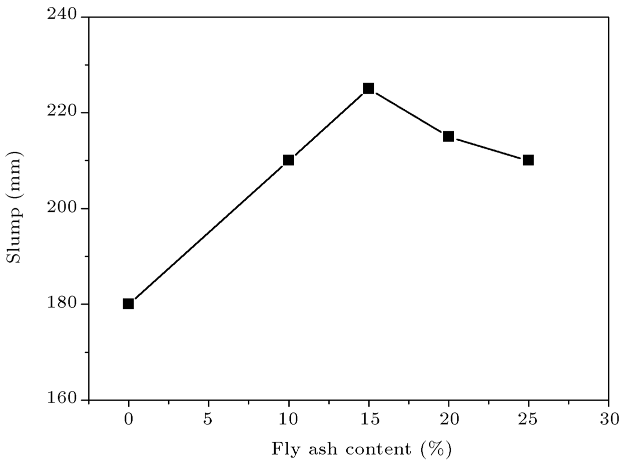

Figure 2. Effect of fly ash content on slump.

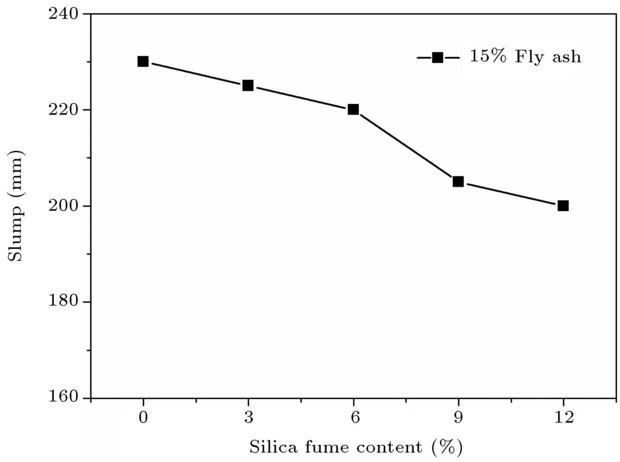

Figure 4. Effect of silica fume content on slump.

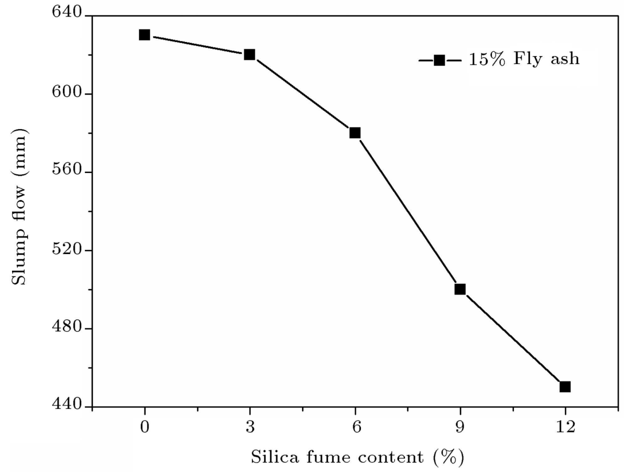

Figure 5. Effect of silica fume content on slump flow.

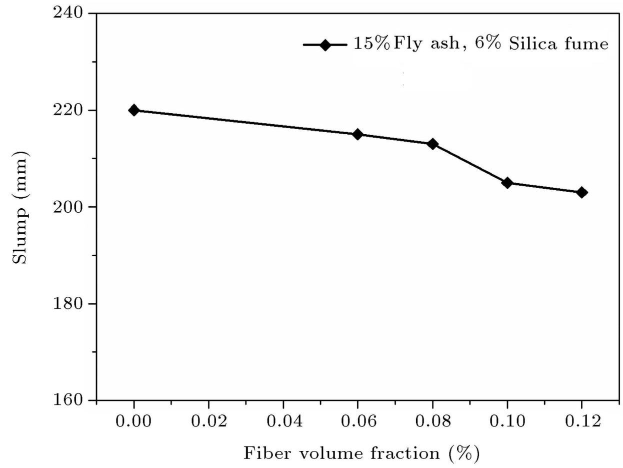

Figure 6. Effect of fiber volume fraction on slump.

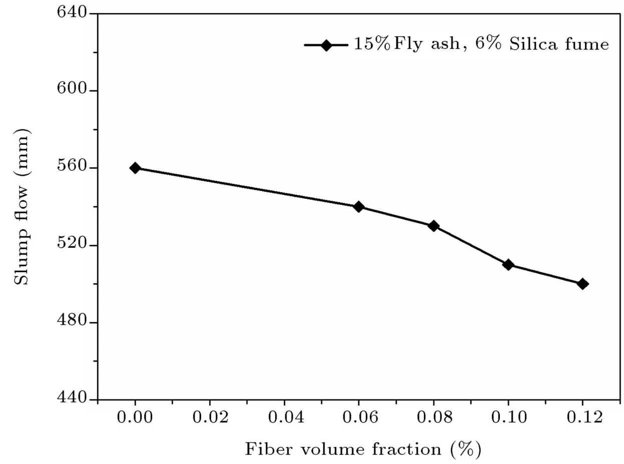

Figure 7. Effect of fiber volume fraction on slump flow.

15% fly ash, which indicates that the addition of silica fume has adverse effect on the workability of concrete composite containing fly ash. Compared with the concrete composite without silica fume, decrease of the slump and slump flow were determined as 13% and 28.6% for the concrete composite with 12% silica fume content, respectively. With the increase of silica fume content, both the slump and slump flow decrease gradually, however, the effect of silica fume on the workability is not obvious when the silica fume content is less than 6%. There is a great decrease in the slump and slump flow when the silica fume content increases from 6% to 9%, and the decrease rate in the slump and slump flow becomes smaller after the silica fume content exceeds 9%. The higher demand of water with the concrete containing silica fume can be attributed to the very fine particle size of silica fume that causes some of the water being adsorbed on its surface [28]. It is worth adding that mixes incorporating more silica fume were more cohesive, and this is in agreement with the findings of Khatri and Sirivivatnanon [29]. The main reason why the addition of silica fume decreases the workability of concrete composite containing fly ash is that the grain size of silica fume particle is smaller than that of the fly ash and cement, and the fresh concrete has high viscidity with the addition of a large number of silica fume particles.

3.1.3. Effect of fiber volume fraction on the slump and slump flow

Figures 6 and 7 illustrate the variations of the slump and slump flow of the concrete composite with 15% fly ash and 6% silica fume with the increase of polypropylene fiber volume fraction, respectively. It can be seen from the figures that the addition of polypropylene fiber decreases the slump and slump flow of the concrete composite with 15% fly ash and 6% silica fume. With the increase of fiber volume fraction, both the slump and slump flow decrease gradually. Compared with the concrete composite without polypropylene fiber, the decrease of the slump and slump flow were determined as 7.7% and 10.7% for the concrete composite with 0.12% fiber volume fraction, respectively. For the slump, there is a sharp decrease when the fiber volume fraction increases from 0.08% to 0.1%. With the increase of fiber volume fraction, the number of fibers in unit concrete mixture becomes larger, and the water absorbed on the surface of the fibers becomes more. Therefore, the obstructive effect of fibers on the flowability of fresh concrete becomes much larger. The addition of polypropylene fiber may be adverse to the workability of fresh concrete containing fly ash and silica fume. The existing research results have drawn the same conclusion on concrete without fly ash and silica fume [30].

3.2. Drying shrinkage

3.2.1. Effect of fly ash content on drying shrinkage

Drying shrinkage tests can provide necessary information on how the drying shrinkage stresses develop, although they cannot offer sufficient information on

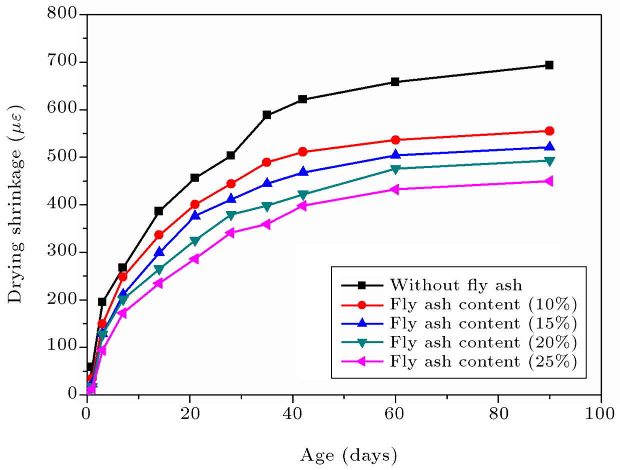

Figure 8. Effect of fly ash content on drying shrinkage.

the behavior of concrete structure [31]. Figure 8 shows the varying rules of the relational curves between drying shrinkage strain of the beam specimen of fly ash concrete and the curing age, as the content of fly ash varies. As seen in Figure 8, the shrinkage values yielded approximately comparable values at early ages of drying period. However, a clear distinction was observed for different concretes after about ten days. It was clearly observed in Figure 8 that the concretes with 10%, 15%, 20% and 25% fly ash had lower shrinkage strain than the control concrete, when the fly ash content is not beyond 25%. In other words, the anti-drying-shrinkage cracking property of concrete composite may be improved with the addition of fly ash. This beneficial effect appeared to be more pronounced with increasing the replacement level of fly ash. As the fly ash content increase from 0 to 25%, the maximum drying shrinkage strain of 90 days ages decreases 35% from 693 $\mu\varepsilon$ to 450 $\mu\varepsilon$. When the curing age is less than 42 days, the increasing rate of the drying shrinkage strain is higher with the curing period age increasing, while the increasing rate is much lower when the curing age is beyond 42 days. In other words, the contribution of fly ash on the anti-drying-shrinkage cracking property of concrete composite may be larger on the later ages. The incorporation of fly ash has been found to reduce the shrinkage of mortar [32]. The addition of fine particles of fly ash caused the segmentation of large pores, and increased the nucleation sites for precipitation of hydration products in cement paste resulting in the pore refinement [33]. Fly ash addition also contributed to the better cohesion of the fresh mixture and lower early plastic shrinkage deformations [34]. When the fly ash content is high, the cement paste can be considered as a multiphase composite material, and there is a part of fly ash unreacted. The unreacted fly ash particles in the paste may act as micro-aggregates with higher modulus of elasticity, which increase the resistance to crack propagation [35]. The increasing resistance to crack propagation also reflects the increasing resistance shrinkage of the concrete composite with the increase of fly ash content.

3.2.2. Effect of silica fume content on drying shrinkage

Drying shrinkage with curing age is shown in Figure 9 for different concretes with constant fly ash content of 15% and different silica fume content. From Figure 9 it can be seen that the drying shrinkage strain in the fly ash cement concretes, containing silica fume, was more than that in the fly ash cement concrete without silica fume, and a considerable increase in the drying shrinkage strain of the concrete, containing fly ash, was observed by increasing the dosage of silica fume. In other words, the addition of silica fume may have adverse effect on the anti-drying-shrinkage cracking property of concrete composite containing fly ash. This adverse effect appeared to be more pronounced with increasing the replacement level of silica fume. The trend of the data in Figure 9 agrees well with what has been reported earlier by other researchers [36,37]. Compared with the fly ash concrete without silica fume, the increase of maximum drying shrinkage strain of 90 days ages was determined as 28% for 12% silica fume content. The variation trend of drying shrinkage values with the increase of drying period of concretes, containing silica fume and fly ash, is similar to that of the concretes containing only fly ash. That is, the shrinkage values yielded approximately comparable values at early ages of drying period, however, a clear distinction was observed for different concretes after about ten days. Silica fume may be due to the greater chemical shrinkage than that of the concrete with pure Portland cement. Thus, the greater shrinkage led to faster and greater self-desiccation, and resulted in larger drying shrinkage [38]. Moreover, the use of silica fume makes a cement paste have a finer pore structure,

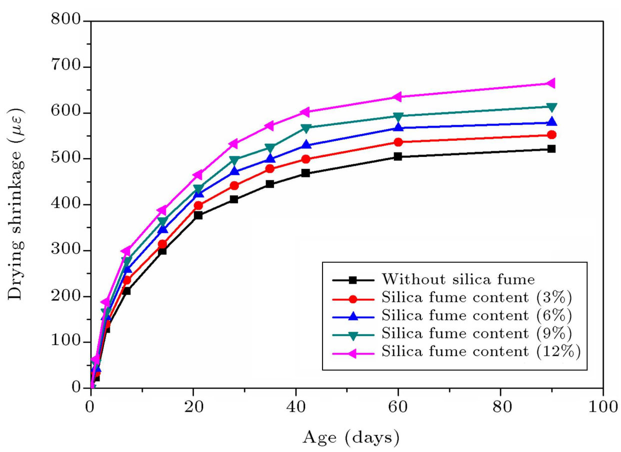

Figure 9. Effect of silica fume content on drying shrinkage.

as confirmed by permeability [39]. Finer pores contribute to a lower relative humidity, which increases the degree of self-desiccation within the cement paste.

3.2.3. Effect of fiber volume fraction on drying shrinkage

The results of drying shrinkage or shrinkage strain of 15% fly ash and 6% silica fume concrete samples containing 0%, 0.06%, 0.08%, 0.10%, 0.12% polypropylene fibers are presented in Figure 10. As can be seen from Figure 10, the addition of polypropylene fibers in the concrete containing fly ash and silica fume reduces the drying shrinkage considerably. Malhotra et al. [40] concluded that polypropylene fiber reinforced high volume fly ash concrete has very low drying shrinkage property. Liu et al. [41] and Salih and Al-Azaawee [42] stated that polypropylene fiber mixed into cement mortar decreased its drying-shrinkage. They concluded that the reduction in drying shrinkage increases with increasing the percentage of volume fraction of fiber. Okan and Cengiz [43] supported this finding and reported that the use of polypropylene restrained the movements of micro level in mortar by bridging and stitching the fine cracks. There is a tendency of decrease in drying shrinkage strain, with the increase of fiber volume fraction. As the fiber fraction of polypropylene fiber inreases from 0 to 0.12%, the maximum drying shrinkage strain of 90 days age decreases 24% from 579 $\mu\varepsilon$ to 441 $\mu\varepsilon$. One reason for the beneficial influence of polypropylene fibers is given by Mangat and Azari [44]. When the matrix is subjected to tensile stresses induced by shrinkage, fibers restrain shrinkage by shear along the fiber-matrix interface. Polypropylene fibers can offset a part of tensile stress caused by the drying shrinkage of the cement paste because polypropylene fiber has high tensile strength and high deformability, and the fibers indirectly reduce the shrinkage stress inside the concrete by decreasing the stress concentration of shrinkage stress. As a result, the drying shrinkage decreases when polypropylene fibers are added into concrete containing fly ash and silica fume.

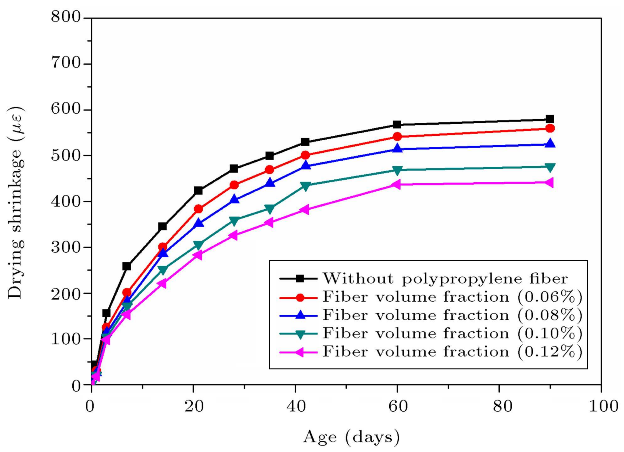

Figure 10. Effect of fiber volume fraction on drying shrinkage.

4. Conclusions and further recommendations

This paper reported experimental results of the workability and drying shrinkage studies conducted on fly ash and silica fume concrete composite reinforced with polypropylene fiber. The following results were obtained from this study:

1. Fly ash has great effect on the workability and drying shrinkage of concrete composites. Both the slump and slump flow of the concrete composite were increased by increasing the fly ash content with the fly ash content not beyond 15%. After the content of fly ash increases continuously from 15% to 25%, both the slump and slump flow become lower gradually, however, the values of the slump and slump flow are still higher than that of the concrete without fly ash. The addition of fly ash has restricted the drying shrinkage of concrete composite, and the drying shrinkage strain of the concrete for each curing age is decreasing gradually with the increase of fly ash content with the fly ash content not beyond 25%.
2. Addition of silica fume has adverse effect on the workability and drying shrinkage property of concrete composite containing fly ash. With the increase of silica fume content, both the slump and slump flow decrease gradually, however, the effect of silica fume on the workability is not obvious when the silica fume content is less than 6%. There is a great decrease in the slump and slump flow when the silica fume content increases from 6% to 9%, and the decrease rate in the slump and slump flow becomes smaller after the silica fume content exceeds 9%. The drying shrinkage strain in the fly ash cement concretes containing silica fume was more than that in the fly ash cement concrete without silica fume, and a considerable increase in the drying shrinkage strain of the concrete containing fly ash was observed by increasing the dosage of silica fume.
3. Addition of polypropylene fiber decreases the slump and slump flow of the concrete composite with 15% fly ash and 6% silica fume. With the increase of fiber volume fraction, both the slump and slump flow decrease gradually. However, the addition of polypropylene fibers in concrete containing fly ash and silica fume reduces the drying shrinkage considerably, and there is a tendency of decrease in drying shrinkage strain with the increase of fiber volume fraction as the fiber volume fraction is not beyond 0.12%.

4. Beside the workability and drying shrinkage properties, the other mechanical properties and durability of polypropylene fiber reinforced concrete containing fly ash and silica fume are also important for the application of this concrete composite, and these properties should be studied in the further research work. Furthermore, the effect of the types of fly ash, silica fume and polypropylene fiber on the drying shrinkage properties of the concrete containing fly ash and silica fume is also the important study works in the future research.

Acknowledgments

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