SHRINKAGE PROPERTIES OF POLYOLEFIN FIBER REINFORCED MORTARS

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Summary: In this study some experimental programs were carried out to investigate the influence of application of polyolefin fibers on plastic shrinkage cracks, drying shrinkage, and restrained shrinkage of mortar under laboratory. A mortar mix was evaluated at two different polyolefin fiber contents and without fibers. The test results show that adding polyolefin fibers to the mortar mix can arrest plastic shrinkage cracks and cause a decrease in drying shrinkage whereas they affect the flexural strength slightly.

1 INTRODUCTION

As long as concrete is restrained from shrinkage freely, tensile stresses form. These stresses and low fraction of concrete strength may lead to cracking [1-4]. Because of the fact that cracks accelerate the penetration of aggressive agents into concrete, they cause a major concern in large flat structures such as highways, bridge decks, and industrial floors [5-8]. The cracks can be favorably modified by adding short, randomly distributed fibers of various suitable materials. Fibers not only suppress the formation of cracks, but also abate their propagation and growth [9].

Plastic shrinkage occurs during the first few hours subsequent to placing when the evaporation of water from the concrete surface is greater than the bleeding rate. At this time, if the concrete is subjected to some forms of restraint such as steel reinforcement and the concrete below the drying surface, tensile stresses develop in the plastic concrete and result in cracking [10, 11]. Banthia and Yan [12] carried out a comprehensive investigation on the plastic shrinkage behavior of polyolefin fiber reinforced concretes at different geometries and volume fraction. They showed that fibers with a higher aspect ratio are generally more effective in controlling plastic shrinkage cracking. They also introduced a new parameter, specific fiber surface, which is defined as the fiber surface area in a unit volume of the concrete and can be a better indication of fiber performance.

Drying shrinkage is mainly related to the removal of adsorbed water from C-S-H layers in the hydrated cement paste [13]. There are lots of researches on the effects of fibers on drying shrinkage however there is not a strong consensus among the researchers. Zollo [14], Litvin [15], and Al-Tayib et al. [16] have reported that there is a reduction in the drying shrinkage by using polypropylene fibers, on the other hand, Aly et al. [17] and Altoubat and Lange [18] indicated that polypropylene fiber reinforced specimens exhibited higher total shrinkage strains compared with plain concrete. Swamy and Stavrides [19] have reported that the influence of fiber addition on drying shrinkage is relatively insignificant and depends on the amount and geometry of the fiber inclusions, the type of specimen and the richness and type of matrix.

When shrinkage is restrained, fiber reinforcement delays the formation of the first crack and reduces the crack widths considerably. Further, the sudden failure observed with unreinforced matrices is prevented by development of multiple cracking. The fiber reinforced specimens were able to resist 50-100% more tensile stresses, and continued to sustain the stresses even after 8 to 12
months [19]. Grzybowski and Shah [20] showed that the amount of fibers as small as 0.25 % by volume can substantially reduce crack widths resulting from restrained drying shrinkage.

Polyolefin fibers as an innovative solution to improve the engineering characteristics of concrete have expected to be one of the fastest growing sectors of the synthetic fiber industry. Polyolefin fibers produced from polypropylene or polyethylene polymers enhance the properties such as shrinkage cracking resistance, flexural strength, toughness, etc.

The objective of this study was to provide a comparative assessment of the effect of polyolefin fibers on the volume changes of concrete. Three tests were conducted as followings: plastic, drying, and restrained shrinkage.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mix proportions

Ordinary Portland cement conforming to ASTM type II was used in all mixes. River sand with fineness modulus of 3.51 and specific gravity of 2.62 were used. In addition, to improve the workability, a commercially available polycarboxylate based superplasticizer (SP) was employed at 0.5% by weight of cement. Polyolefin fibers with a length of 48 mm, aspect ratio of 39, and density of 0.91 g/cm³ were used for the mortar reinforcement. This type of fiber had a tensile strength of 550 MPa and was embossed to increase the bonding of fibers with cement paste (Figure 1). Polyolefin fibers were added at two different dosages of 3 and 6 kg/m³. The details of mix proportions used in this study and the average of compressive and flexural strengths of the specimens are given in Table 1.

The mixing was conducted in a 0.1 m³ conventional pan mixer. First, the sand and cement were placed in the mixer and dry mixed for 1 min. Then, the mixing water with superplasticizer was added and mixing was continued for another 2 min. The fibers were then added gradually to the running mixer and followed by 2 min of final mixing to avoid fiber balling and to produce a homogenous mix.

Table 1: Mix proportions and mechanical properties at 28 days

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Cement (kg/m³)</th>
<th>Water</th>
<th>Sand (kg/m³)</th>
<th>Fiber content (kg/m³)</th>
<th>SP</th>
<th>Slump (cm)</th>
<th>Compressive strength (MPa)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO-0</td>
<td>400</td>
<td>180</td>
<td>1800</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>30.2</td>
<td>5.4</td>
</tr>
<tr>
<td>PO-3</td>
<td>400</td>
<td>180</td>
<td>1800</td>
<td>3</td>
<td>2</td>
<td>11</td>
<td>31.3</td>
<td>6.2</td>
</tr>
<tr>
<td>PO-6</td>
<td>400</td>
<td>180</td>
<td>1800</td>
<td>6</td>
<td>2</td>
<td>9</td>
<td>32.6</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Figure 1: Polyolefin fibers used in this study
2.2 Test methods

Compressive strength test was carried out on three 150 mm cubes for each mixture in accordance with BS-1881. Flexural strength test was performed on three prismatic specimens with dimensions of 100 x 100 x 500 mm for each mixture using the third point loading procedure according to ASTM C1018.

For plastic shrinkage tests, the plywood mold with a depth of 85 mm and rectangular dimensions of 360 by 560 mm was used. The mold was provided with a stress riser of 63.5 mm height at the center and two base restraints of 32 mm height at 90 mm from both ends, along the transverse direction (Figure 2.a). After casting, the mortar specimens were kept for 24 h in an environmental chamber with a temperature of 36 ± 2 ºC, a relative humidity of 24 ± 4%, and wind speed of 6 m/s over the entire surface area of the specimens. Commercially fans and heaters were utilized to achieve the specified environmental conditions. The interior conditions of the environmental chamber with dimensions of 2 x 1 x 1.5 m were monitored by temperature and relative humidity sensors, as shown in Figure 2.b. Under these conditions, an average evaporation rate of 2 kg/m²/h from the water surface was measured using plastic pans placed next to the specimens. The specimens were inspected visually for any signs of cracking at approximately 30 min intervals. In plastic shrinkage test, two specimens, one plain mortar and the other one fiber reinforced mortar were prepared and exposed to identical restraint and environmental conditions. For each fiber dosage, two tests were done and the results were averaged.

Figure 2: Plastic shrinkage setup (a) mold with the stress risers (b) environmental chamber

Drying shrinkage test was carried out on 75 x 75 x 280 mm prisms, two specimens for each mixture. The specimens were demolded at the age of 24 h and placed immediately in lime saturated water at the temperature of 23 ± 0.5 ºC for a minimum of 30 min. After that, the initial measurements for the length were recorded and the specimens were kept in a drying room at 23 ± 1 ºC and 50 ± 5% relative humidity for a period of 56 days.

Restrained shrinkage test was conducted in conformity with AASHTO PP 34-99. This test comprised an annulus of mortar with a thickness of 76 mm placed around a rigid steel ring 12.5 mm in thickness with an outer diameter of 305 mm and a height of 152 mm. After 24 h, the outside plastic mold was removed and the top surface of the mortar ring was sealed by silicone rubber. The specimens were stored at the temperature of 23 ± 1 ºC and relative humidity of 50 ± 5% and checked visually twice a day for any occurrence of cracks. For each mixture, two replicate specimens were made. The restrained shrinkage test setup is shown in Figure 3.
3 RESULTS AND DISCUSSION

3.1 Mechanical properties

The results of compressive and flexural strength tests for plain and fiber reinforced mortars are given in Table 1. The inclusion of polyolefin fibers in the mortar mixtures did not significantly influence the compressive strength. The results indicate that there is a 14% improvement in flexural strength with 3 kg/m$^3$ of polyolefin fiber compared with plain mortar, and increasing the fiber dosage up to 6 kg/m$^3$ had no more effect on the flexural strength.

3.2 Plastic shrinkage

In order to measure the crack characteristics including maximum crack width, average crack width, and total crack area, an image analysis technique was applied. For each specimen, 8 images were captured along the crack length using a digital camera and the overlapping portion of images is cut off. The modified images were attached together and create the whole cracked region. The crack width is calculated by multiplying the number of pixels counted at 10 pixels intervals perpendicular to the crack length by a scale factor. To measure the total crack area, the number of pixels belonged to cracks is multiplied by the square of scale factor. The analysis results for different dosages of polyolefin fibers are given in Table 2.

Addition of fibers affects the cracking characteristics induced by plastic shrinkage noticeably. The crack widths and total crack area decreased with increasing the fiber dosage. The images of plain and polyolefin fiber reinforced mortars are shown in Figure 4. As seen, for plain mortar a single crack in direction normal to the long dimension of specimen was observed while in the case of fiber reinforced specimens, hair line cracks branching out from the main crack were appeared. Polyolefin fibers at dosage of 6 kg/m$^3$ performed remarkably well compared with 3 kg/m$^3$ in terms of reducing the crack dimensions and restricting the crack propagation. At fiber dosage of 3 kg/m$^3$ reduced the maximum crack width by 44% to less than 1.06 mm relative to plain specimen, and for 6 kg/m$^3$ the reduction was at least 99%. For polyolefin fiber reinforced specimens with 3 kg/m$^3$ fiber dosage, the reduction of total crack area was obtained 51% relative to plain mortar specimen, while the specimens with 6 kg/m$^3$ decreased the total crack area by at least 99%.
Table 2: Plastic shrinkage results of plain and polyolefin fiber reinforced mortars

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Time of first visible crack (min)</th>
<th>Average crack width (mm)</th>
<th>Maximum crack width (mm)</th>
<th>Total crack area (mm²)</th>
<th>Percent reduction of crack width (%)</th>
<th>Percent reduction of crack area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO-0</td>
<td>95</td>
<td>0.967</td>
<td>1.884</td>
<td>356.12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PO-3</td>
<td>110</td>
<td>0.505</td>
<td>1.059</td>
<td>173.27</td>
<td>48</td>
<td>51</td>
</tr>
<tr>
<td>PO-6</td>
<td>no crack</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>~100</td>
<td>~100</td>
</tr>
</tbody>
</table>

3.3 Drying shrinkage

The results of drying shrinkage tests for plain and polyolefin fiber reinforced mortars are presented in Figure 5. The shrinkage of fiber reinforced mortars with dosages of 3 and 6 kg/m³ was 11% and 14% less than plain specimen at the age of 56 days, respectively.

There are a number of researchers who subscribe to the view that using fibers in concrete and mortar causes a decrease in drying shrinkage. Zollo [14], Litvin [15] and Al-Tayyib et al. [16] reported that there is a reduction in the drying shrinkage of polypropylene fiber reinforced concrete as compared to plain concrete. In contrast to all, some results of researchers show that adding fibers has no significant effect on the drying shrinkage or even lead to an increase in the drying shrinkage. For instance, Aly et al. [17] reported that polypropylene fiber reinforced specimens exhibited higher total shrinkage strains compared with the plain concrete with no fiber until the age of 56 days. The results demonstrate that the contribution of the polypropylene fibers to permeability of concrete is significant and hence more vulnerable to drying during the shrinkage test. In addition, a study carried out by Altoubat and Lange [18] indicated that fiber reinforcement had only a minor effect on shrinkage. Using polypropylene fibers slightly increased the free shrinkage of concrete, while steel fibers did not influence the free shrinkage.
3.4 Restrained shrinkage (ring test)

During exposure time of 50 days to temperature of 22 °C and relative humidity of 40%, the whole circumferential surface of the specimen was visually inspected and no cracking was observed in plain and fiber reinforced mortars. It can be attributed to the factors including the value of drying shrinkage, aggregate cement ratio, type of cement, etc. An investigation by Whiting et al. shows that the probability of cracking reduces as long as the value of drying shrinkage is less than 550 micro strains \[21\]. Owing to the results of drying shrinkage which obtained in this study, the potential of cracking in both plain and fiber reinforced mortars reduced dramatically, for the specific ring thickness used in this study. It is envisaged that the thickness of steel ring plays a crucial role in time of cracking.

4 CONCLUSIONS

This paper reports experimental results of plastic, drying, and restrained shrinkage tests on plain and polyolefin fiber reinforced mortars at two fiber dosages. The following conclusions can be drawn from the results presented in this paper:

- The flexural strength of polyolefin fiber reinforced mortar with 3 kg/m\(^3\) increased by 14% compared with plain mortar, however no improvement was observed by increasing the amount of fiber to 6 kg/m\(^3\).
- Application of polyolefin fibers at dosage of 3 kg/m\(^3\) reduced the maximum crack width and total crack area by 44% and 51%, respectively. In the case of 6 kg/m\(^3\), no cracks were detected.
- At the age of 56 days, there was a reduction of 11% and 14% for fiber reinforced mortars with dosages of 3 and 6 kg/m\(^3\), respectively.
- For restrained shrinkage test, no cracks were appeared within 50 days of exposure to the specified environmental conditions.

REFERENCES