# Comparison of the Performance of Macro-Polymeric Fibers and Steel Fibers in Controlling Drying Shrinkage Cracks of Concrete

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***Abstract*—When concrete element is exposed to the environment, it undergoes volumetric contraction due to the drying shrinkage, which when restrained can lead to cracking. Crack width is controlled by the ability of fibers in transmission of stress across the crack opening. In this study the effect of Macro polymeric fibers in controlling drying shrinkage cracking of concrete was investigated and compared with that of steel fibers. The results of restrained ring tests show that at low and medium rate of utilization (0.25 and 0.5%) the effect of macro synthetic fibers are similar to steel fibers. However, at a higher dosage of 1%, steel fibers clearly outperform the polymeric fibers. The shape of macro polymeric fibers (multi-strand or single-strand) was not found to significantly affect their performance.**

***Index Terms*—concrete, drying shrinkage, macro polymeric fiber, steel fiber, restrained ring**

## I. Introduction

Concrete is the most widely used material in civil engineering due to its numerous technical and economical benefits however, concrete also has shortcomings which have to be considered in its application. Upon exposure to environment, it undergoes volumetric contraction due to the drying shrinkage, which when restrained can lead to cracking [1, 2, 3].

Drying shrinkage cracking control is an important factor for concrete structures such as slab on the ground. Concrete slabs include industrial floors, pavement and so on [4, 5, 6, 7]. Contraction joints have to be provided spacing of, which depends on concrete shrinkage, slab thickness and ground restraint degree. With the use of reinforcement such as steel mesh, the spacing of joints can be increased [6, 8].

By development of fiber concrete technology, it is now possible to replace the mesh with the fibers and achieve benefits such as avoiding mesh placement operations and increased construction speed. This has attracted the designers and particularly contractors to consider the use of fibers. Giving that the different kind of fibers such as steel fibers, micro polymeric fibers and recently macro polymeric fibers are available, the comparison of the performance of various fibers in different dosages has been considered by many researchers. Micro polymeric fibers usually have a length less than 25 mm and the diameter is in the range of 20 to 100μm. Regarding the control of drying shrinkage cracking previous investigations indicate that considering the limitation of the maximum useable amount of micro polymeric fibers which is approximately 0.25%, these fibers could not be expected to function comparable to steel mesh [9, 10]. In the case of steel fibers, it has been determined that these fibers function effectively in delaying the cracking time as well as reducing crack opening. However, these effects depend on the fiber content [10, 11, 12]. A previous research shows that at dosage of 0.25 and 1 percent (by volume), steel fiber can reduce the width of the cracks caused by drying shrinkage to 0.25 mm and 0.1 mm, respectively compared to the 1 mm width of the crack in the control mix [13].

Macro polymeric fibers are more recent developments compared to micro polymeric and steel fibers. These fibers have a length of approximately 30 to 60 mm and according to standard ASTM C1116 [14] macro fibers diameter are more than 0.3 mm. The larger dimension of macro polymeric fibers allows them to be used in greater volume compared to micro fibers. Some companies that produce these fibers claim that macro polymeric fibers to be very effective in reducing shrinkage cracking. Some investigations however indicate a weaker performance of these fibers in comparison of steel fibers in equal amount of consumption [15]. Voigt et al observed that at low dosage (approximately 0.25), there is no significant difference between steel and polymeric fibers for delaying of cracking time. Comparing the performance of these fibers at higher levels of consumption however showed better performance of the steel fibers [10]. Recent research by Yousefieh, Joshaghani, Hajibandeh and Shekarchi which was limited to a maximum of 0.2% uses of macro polymeric fibers as expected showed little effect in postponing of drying shrinkage cracking time [16]. A recent review article published by Yin et al. [17] regarding to the performance the fibers, indicates that there is currently no definite conclusion on this issue. With regards to free drying shrinkage it has become

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apparent that the use of fibers does not decrease this parameter [18].

## II. Experimental Investigation

### A. Mixes Considered

The aim of the experimental study was to compare the performance of steel and macro polymeric fibers in various dosages in controlling drying shrinkage cracks in concrete. One type of steel fiber and two different types of macro polymeric fibers were used in this study. The fiber dosages considered were 0.25, 0.5 and 1 % (by volume). In addition, one type of micro polymeric fiber at dosage of 0.25% was investigated. The experimental program involved the evaluation of 11 concrete mixes including the mix without fiber (control mix). Restrained ring test according to ASTM C1581[19] and free shrinkage test according to ASTM C157 [20] were carried out to evaluate the performance of various mixes. Additionally, tensile and compressive strength tests were carried out.

### B. Materials

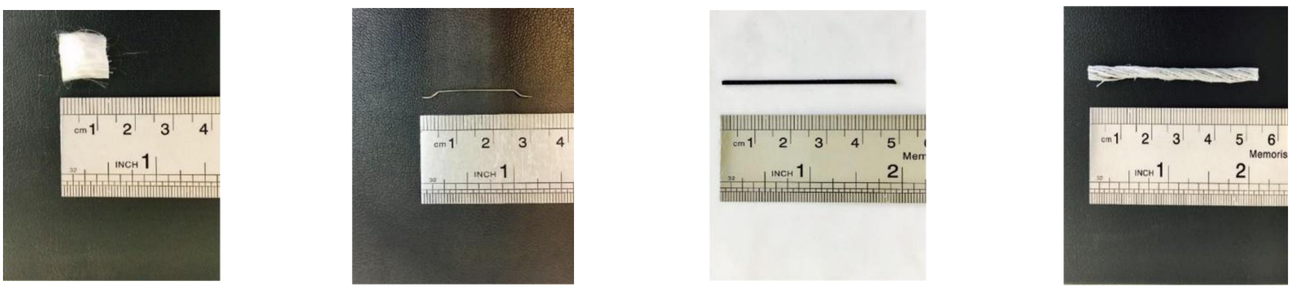
1) *Cement.* Portland cement produced by Tehran cement factory conforming with the requirements of ASTM C150 [21] for type 2 cement was used in this study.

2) *Aggregates.* A river sand with a maximum nominal size of 4.75 mm was used as fine aggregates. A crushed gravel was used as coarse aggregate and in order to comply with the ASTM C1581 [19] maximum gravel size was limited to 12.5 mm. Aggregates grading were in accordance with ASTM C33 [22].

3) *Fibers.* Fibers used included, a hooked end steel fiber, micro polymeric fiber, macro polymeric fiber of single-strand type and macro polymeric fiber of spun multi-strand type. The fibers used and their characteristics are depicted in Fig. 1, and Table I, respectively.

TABLE I. Characteristics of Fibers Used

| Fiber properties | Fiber type | | | |
|---|---|---|---|---|
| | Forta multi-strand macro fibers | Single-strand macro fibers | Steel fiber | Micro polymeric fiber |
| Brand | Forta ferro | Barchip | Dramix | PP |
| Material | Polypropylene | Polypropylene | Steel | Polypropylene |
| Color | Gray | Black | Silver | White |
| Shape | Spun multi-strand | Single-strand | Hooked | Fibrilated |
| Specific gravity | 0.91 | 0.91 | 7.81 | 0.91 |
| Length ($mm$) | 50 | 50 | 35 | 12 |
| Diameter ($mm$) | 0.34 | 0.5_1 | 0.55 | 0.02 |
| Tensile strength ($MPa$) | 693 | 640 | 1150 | 300 |
| Melting point (℃) | 165 | 159-179 | 1500 | 160-165 |
| Modulus of elasticity ($GPa$) | 6.4** | 1.4** | 210* | 3_10* |



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

Figure 1. Fibers pictures used. Micro polymeric fibers, PP (a), Steel fiber (b), Macro polymeric fiber, Black barchip (c), Macro polymeric fiber, Forta (d)

The elastic modulus of macro polymeric fibers was determined in accordance with ASTM C1557 [23] (Fig. 2).

### C. Concrete Mixture Composition

The base mix composition was the same for all mixtures and the required dosages of fibers were added to base mixture. Therefore cement content and water cement ratio were similar for all mixes at $400\,\mathrm{kg/m^3}$ and 0.46, respectively. Workability was kept constant for all mixes at a slump of $7\pm2\mathrm{cm}$. In order to compensate for loss of workability due to fiber addition, superplasticizer content of mixes were varied as needed to achieve the target slump value. The properties of mix composition are shown in Table II.

*D. Test Methods*

*1) Mechanical characteristics.* Compressive strength of mixtures was determined according to standard 320 of Iran on 10 cm cubic test specimens at 28 days. Tensile strength of different mixtures was determined in accordance with ASTM C496 [24] on cylindrical specimens of $10\times20\mathrm{cm}$ at 28 days.

Figure 2. Test for determining the Young's modulus of polymeric fibers

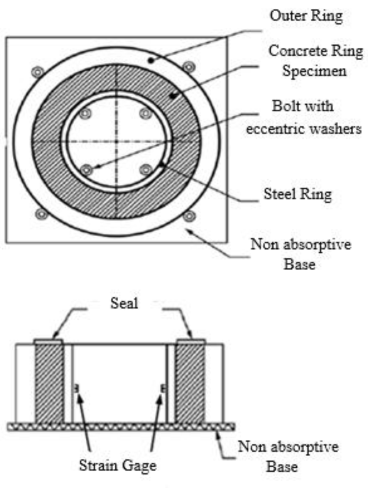
*2) Free shrinkage.* Free shrinkage test was carried out on prismatic specimens of $75\times75\times275\mathrm{mm}$ in accordance with ASTM C157 [20]. After being moist cured for 7 days, specimens were placed in the testing environment at the relative humidity of $50\pm5\%$ and free shrinkage values were measured at different times.

*3) Restrained shrinkage.* Although researchers have used various tests to evaluate potential for restrained shrinkage cracking [25], the only standard test on this issue is the restrained ring test in accordance with ASTM C1581 [19]. This test method was used to evaluate the performance of different mixes in this study. The equipment of restrained ring test include an inner steel ring with a wall thickness of 15 mm, outside diameter of 325 mm and with height of 150 mm. A steel ring with diameter of 405 mm is used as an external mold (Fig. 3a). After casting specimens, the surface of the specimens were covered by polypropylene sheet immediately to prevent drying. After 24 hours, the external mold was removed and the surface of the specimens were sealed by paraffin. In this way the specimen were subjected to drying from the outer circumferential surface only. Two strain gages, which were connected to data acquisition system had been bonded on the interior surface of the steel ring along a diameter to measure strain in the circumferential direction (Fig. 3b).

*3.1) Determination of the time of cracking.* Drying shrinkage of the concrete ring induces compressive strains on the steel ring which is measured by the strain gages bonded on the inner surface of the steel ring and recorded by the data logger. A sudden decrease in measured compressive strain would therefore indicate cracking of the concrete ring and removal of the compressive strains. This moment is considered as the time of cracking and the age at cracking of each test specimen is determined. Net time to cracking $(t_{cr})$ is the difference between age at cracking and the age that drying was initiated and this parameter is considered as a criterion for the potential for restrained drying shrinkage cracking. According to the ASTM C1581, cracking potential is classified into four categories: High, Moderate-High, Moderate-Low and Low. The mixtures with net time to cracking of less than 7 days have High potential for cracking. If the net time to cracking is longer than 28 days, the cracking potential is considered as Low.

TABLE II. CONCRETE MIXTURE COMPOSITIONS

| Mixes Code | Specific gravity of fresh concrete $(\mathrm{gr/cm^3})$ | Fiber type | Fiber content (Vol%) | Super plasticizr $(\mathrm{kg/m^3})$ |
|---|---|---|---|---|
| Control | 2.291 | - | - | 0.3 |
| Fo-0.25 | 2.315 | forta | 0.25 | 1 |
| Fo-0.5 | 2.31 | forta | 0.5 | 1.6 |
| Fo-1 | 2.295 | forta | 1 | 3.3 |
| Ba-0.25 | 2.317 | barchip | 0.25 | 0.7 |
| Ba-0.5 | 2.32 | barchip | 0.5 | 1 |
| Ba-1 | 2.295 | barchip | 1 | 1.17 |
| PP-0.25 | 2.23 | Micro polymeric | 0.25 | 1.83 |
| St-0.25 | 2.331 | steel | 0.25 | 1 |
| St-0.5 | 2.353 | steel | 0.5 | 1.2 |
| St-1 | 2.373 | steel | 1 | 1.43 |




(a)

(b)

Figure 3. Schematic view of concrete ring specimen and apparatus (a), View of restrained shrinkage test (b)

*3.2) The determination of stress rate in concrete specimen.* According to ASTM C1581, to determine cracking potential, in addition to the net time to cracking, another parameter called stress rate has also been defined. The procedure for determination of the stress rate development is described in ASTM C1581. The cracking potential according to the stress rate is also classified into four categories and if the tensile stress rate of a mix is less than $0.1 \text{MPa/day}$, it's cracking potential is Low. If the stress rate is more than $0.34 \text{MPa/day}$ the cracking potential is considered High.

*4) Evaluation of Crack Width by Crackscope.* In addition to strain monitoring of steel rings, the concrete ring surface were also periodically examined by crackscope for observing cracks and measuring their width. Maximum crack opening for each mixture were measured at 28 days by crackscope with a precision of 0.05 mm (Fig. 4 and 5). It should be noted that the maximum crack width is an important parameter in evaluating the performance of the fibers in drying shrinkage cracking control.

## III. Experimental Results and Discussion

### A. Compressive and Tensile Strength

In table 3, the results of compressive strength testing of various mixes are presented. The results show that use of steel fibers up to 1% and macro polymeric fibers up to 0.5% have no appreciable effect on compressive strength. However, mixes with macro polymeric fibers contents of 1% showed a decrease in compressive strength. This effect was higher for multi-strand forta fiber compared to the single-strand macro polymeric fiber (barchip). The effect of fibers on tensile strength was found to be similar to that described for compressive strength. However, at the dosage of 1%, steel fibers increased slightly the tensile strength. Due to the high elastic modulus of steel fibers compared to concrete, improving of tensile strength is expected with increasing the dosage of steel fiber. Given that the elastic modulus of polymeric fibers is significantly lower compared to concrete and also the difficulty in distributing these fibers at high dosage, the observed effect of these fibers on tensile strength is expected. The results obtained confirm the previous finding that the effect of fiber addition particularly at low and medium dosages on strength is limited [15, 26].

Figure 4. View of the Crackscope

Figure 5. View of the restrained drying shrinkage crack

### B. Free Shrinkage

Free shrinkage test was carried out for the control mix and mixes containing different fibers at various dosages. The results for mixes with fiber content of 1% are given in Fig. 6. The results indicate that the effect of fibers on the free shrinkage is negligible. Previous study on polymeric fibers by Ideker and Banuelos [18] and research on steel fibers by Shah [12] indicate similar results to the current study.

*C. Restrained Shrinkage*

*1) The time to cracking.* The results show that the use of various fibers at a low dosage (0.25%) has a small effect on increasing the time to cracking. At this dosage, the use of steel fiber has a slightly better performance than other fibers. By increasing the dosage of macro polymeric and steel fibers up to 0.5%, considerable increase in cracking time of various fibers is observed. An increase in the macro polymeric fiber contents up to 1% results in a considerable increase in the cracking time. The time dependent strain diagram of restrained ring test for the control mix and the mixes containing 1% of various fibers are presented in Fig. 7. As shown, a similar result was found by using 1% single-strand fiber (barchip) and multi-strand fiber (forta) and both fibers increased the cracking time of 5.5 days (for control mix) to approximately 21 days. The performance of the steel fiber at the dosage of 1% was better than polymeric fibers and these specimens did not crack during the 28 days. The result of time to cracking for different mixes are given in table 3.

The cracking potential of the mixes based on the cracking time criterion according to the proposed classification by ASTM C1581 [19] is presented in table 3. As shown, the control mix has a high potential for cracking. Using 0.25% of different fibers has a relatively small effect on improving this potential and the mixes mainly have High cracking potential. Increasing the dosage of fibers to 0.5% causes some improvement in the situation and mixes are classified as mixes with Moderate to High cracking potential. With increasing the dosage of fibers to 1% further improvement in performance of macro polymeric fibers is observed and their cracking potential has been evaluated as Moderate to Low. Steel fibers, at the dosage of 1% have the best performance and their cracking potential was determined as Low. In this study, in addition to net time to cracking as a cracking potential criterion, cracking potential was also classified based on tensile stress rate criterion and the results are given in table 3. The performance of various mixes based on the stress rate criterion were found to be similar to that of the time to cracking criterion given above.

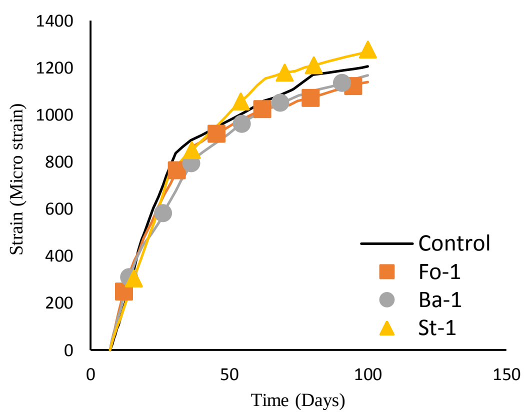



Figure 6. Free shrinkage strain-time diagram for 1% fibers

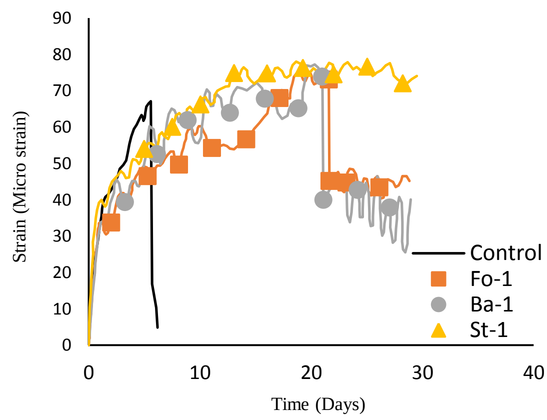



Figure 7. Strain measurement of the steel ring for plain and fiber reinforced concrete (1%)

TABLE III. MECHANICAL PROPERTIES AND CRACKING POTENTIAL OF THE MIXTURES

| Mix Code | Fiber type | Fiber content (Vol%) | Compressive strength $(kg/cm^2)$ | Tensile Strength $(kg/cm^2)$ | Age at cracking (day) | Net time to cracking (day) | Stress rate (S) | Potential for cracking in net time to cracking $(t_{cr})$ | Potential for cracking in stress rate (S) |
|---|---|---|---|---|---|---|---|---|---|
| Control | - | - | 467.5 | 41.38 | 5.6 | 4.6 | 0.42 | H | H |
| Fo-0.25 | forta | 0.25 | 484 | 40.53 | 7 | 6 | 0.36 | H | H |
| Fo-0.5 | forta | 0.5 | 473.5 | 38.84 | 15 | 14 | 0.17 | M-H | M-H |
| Fo-1 | forta | 1 | 344 | 30.56 | 21.6 | 20.6 | 0.11 | M-L | M-L |
| Ba-0.25 | barchip | 0.25 | 467.5 | 39.79 | 6.6 | 5.6 | 0.4 | H | H |
| Ba-0.5 | barchip | 0.5 | 480 | 37.67 | 13.7 | 12.7 | 0.18 | M-H | M-H |
| Ba-1 | barchip | 1 | 389.5 | 38.2 | 21 | 20 | 0.11 | M-L | M-L |
| PP-0.25 | Micro polymeric | 0.25 | 361 | 41.16 | 6.6 | 5.6 | 0.34 | H | H |
| St-0.25 | steel | 0.25 | 484 | 36.28 | 10 | 9 | 0.26 | M-H | M-H |
| St-0.5 | steel | 0.5 | 466 | 44.3 | 12 | 11 | 0.17 | M-H | M-H |
| St-1 | steel | 1 | 475 | 54.32 | no crack was found | $\geq 28$ | 0.08 | L | L |

### D. Maximum Crack Width

By measuring the width of cracks by crackscope the maximum amount of crack opening for each specimen was obtained at 28 days and results are presented in table 4. The maximum crack width for the control mix was measured as 0.75 mm in 28 days. The effect of micro and macro polymeric fibers and also steel fiber at a dosage of 0.25% on the reduction of crack width is relatively low and the amount of crack opening was about 0.5 mm. By increasing the dosage of macro polymeric and steel fibers up to 0.5%, the crack width was approximately 0.4 mm to show a decrease of about 50% in crack width relative to the control mix. By increasing the fibers content to 1%, the maximum crack opening for the macro polymeric fibers was about 0.3 mm which represent a decrease of about 60% in comparison to the control specimen. The steel fibers showed the best performance at the dosage of 1% and were able to completely prevent shrinkage cracking.

TABLE IV. MAXIMUM CRACK WIDTHS AT 28 DAYS

| Mixes Code | Fibers type | Fibers content | Age at cracking (day) | Maximum crack width at 28 days |
|---|---|---|---|---|
| Control | - | - | 5.6 | 0.75 |
| Fo-0.25 | forta | 0.25 | 7 | 0.5 |
| Fo-0.5 | forta | 0.5 | 15 | 0.35 |
| Fo-1 | forta | 1 | 21.6 | 0.3 |
| Ba-0.25 | barchip | 0.25 | 6.6 | 0.5 |
| Ba-0.5 | barchip | 0.5 | 13.7 | 0.4 |
| Ba-1 | barchip | 1 | 21 | 0.3 |
| PP-0.25 | micro polymeric | 0.25 | 6.6 | 0.7 |
| St-0.25 | steel | 0.25 | 10 | 0.45 |
| St-0.5 | steel | 0.5 | 12 | 0.4 |
| St-1 | steel | 1 | no crack was found | no crack was found |

## IV. CONCLUSION

Steel and macro polymeric fibers at the dosage of up to 0.5% have no significant effect on the strength properties of concrete. In the dosage of 1%, the use of macro polymeric fibers caused a moderate reduction in strength properties. However, steel fibers at 1% dosage increased concrete tensile strength.

The use of different polymeric and steel fibers did not have a significant effect on the free drying shrinkage of concrete.

The results of restrained ring test show that addition of various fibers at a low dosage of (0.25%) has little effect on controlling drying shrinkage cracking and the cracking potential of these mixes are classified as High. With increase in the dosage of fibers to (0.5%), the performance of the macro polymeric fibers and steel fibers with regards to cracking potential improves and they are evaluated as mixes with Moderate to High cracking potential. At the fiber content of 1%, steel fibers have the best performance and their cracking potential is classified as Low.

In the terms of controlling the width of shrinkage cracks the effect of steel and macro polymeric fibers are similar at dosage of 0.25% and lead to a reduction of about 35% in crack width. By increasing the fiber dosage to 0.5% performance of polymeric and steel fiber are still similar and maximum crack width is reduced about 50% in comparison with control mix. At the dosage of 1%, steel fiber has a better performance in comparison with polymeric fibers. At this dosage steel fiber reinforced concrete did not crack at 28 days. The mixes containing 1% macro polymeric fibers caused reduction of 60% in crack width in comparison with the control mixture.

Differences in the structure of the two types of macro polymeric fibers used in this study, i.e; the single-strand type (barchip) and the multi-strand type (forta) did not have a significant effect in the their performance and both types of fibers performed similarly.

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