DURABILITY AND DIMENSIONAL STABILITY OF STEEL FIBER REINFORCED CEMENTITIOUS MORTAR IN COMPARISON TO HIGH PERFORMANCE CONCRETE

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ABSTRACT

This paper presents a study on durability and dimensional stability of a Steel Fiber Reinforced Cementitious Mortar (SFRCM), and the results are compared with those of a common High Performance Concrete (HPC) mix. Common mechanical, durability, and dimensional stability properties of the hardened mortars and concrete are investigated by testing water absorption, water penetration, resistance to elevated temperature, thermal expansion coefficient, and drying shrinkage. The results reveal superior mechanical and durability performance of SFRCM in comparison to those of the HPC. However, there were some concerns about the performance of SFRCM exposed to elevated temperatures because of the low porosity and permeation. In addition, the higher thermal expansion coefficient and different shrinkage behavior of SFRCM should be considered in the design of structural elements.

Keywords: Cementitious mortar; concrete; durability; HPC; steel fiber.

1. INTRODUCTION

High performance concrete is currently employed for the construction of infrastructures such as jetties, bridges, tunnels, and skyscrapers in seismic areas where the structural elements are affected by heavy stresses or aggressive environments [1-5]. However, some other types of concrete or mortar could even show a better performance than HPC. The high cost of repair works has led to some attempts by several researchers and engineers to produce other reliable materials. The construction of concrete structures using these cementitious materials

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could extend their service life while maintaining minimal maintenance requirements. Additionally, the longer life of the structures minimizes the environmental impacts of the common materials like cement.

In this study, a Steel Fiber Reinforced Cementitious Mortar (SFRCM) was obtained by eliminating coarse aggregates, using aggregate with an optimized granular mixture, a very low water-binder (w/b) ratio, heat treatment curing, adding steel fibers to improve ductility, and incorporating of silica fume (SF) into the mixture [6].

Brittle materials such as cementitious matrices exhibit low energy absorption because of the small amount of deformation that they can tolerate and their vulnerability to cracking. Steel fibers significantly improve the flexural, tensile, and shear strength of steel fiber reinforced mortars [7]. The fibers bridge cracks during loading, and prevent the growth and joining of the cracks by transferring the loads. Fiber reinforcement has also been shown to reduce shrinkage cracking and permeability under load, and to enhance fatigue resistance [8-12].

The lack of durability of concrete structures in different types of aggressive environments has been reported by numerous researchers over the years [13-19].

The transport mechanisms in concrete, considering the types of attack like chloride and sulfate penetration or carbonation, could involve the permeation of water, absorption of aqueous solutions by capillary suction, and diffusion of gaseous compounds. Therefore, durability concerns certainly need to address the transport properties [20-24].

In the current study, durability and dimensional stability indexes including water absorption, water suction porosity, water penetration depth, resistance to elevated temperature, thermal expansion coefficient, and shrinkage of three mixes were investigated. Two SFRCM mixes with different fiber contents (1% and 2% of mortar volume), and a common HPC mix were produced in the lab, and test results were compared.

Despite the various benefits of fiber reinforcement, fibers can also make cementitious mortars difficult to handle in the fresh state since mixing and casting become more difficult; this could impact hardened state properties by causing excessive voids as well as difficulties with the fiber dispersion and a reduction in the strength and durability of the material [25-26]. Therefore, the role of fiber content in the durability and dimensional stability of the specimens was investigated as well.

### 2. RESEARCH SIGNIFICANCE

SFRCM seems to be a promising material in the construction of extraordinary buildings which demand a very high performance in terms of mechanical strength, ductility as well as durability. However, different aspects of their performance should be studied before being widely utilized in the construction especially in aggressive and hot environments. In these circumstances, the durability and dimensional stability must be considered as one of the most important design concerns. It would be interesting to study these properties of SFRCM and compare the results with a common high performance concrete which its behavior is almost well-understood.
3. EXPERIMENTAL PROGRAM

3.1 Materials
Type 1-52.5 ASTM Portland cement with a Blaine fineness of 3200 cm²/gr was used in this study for achieving the highest possible strength. A white undensified silica fume (SF) with low carbon content (0.3 percent of weight) was used as a mineral additive for enhancement in the mechanical and durability performance of the mixes. The chemical properties of the used cement and silica fume are presented in Table 1.

A well-graded crushed silicious aggregate with the maximum grain size of 19 mm was used as coarse aggregate for HPC mix; in addition, a basalt aggregate with a maximum grain size of 2 mm was used in SFRCM mixes. A poly carboxilate based superplasticizer was also employed in all mixes to achieve a desirable workability.

Straight brass coated steel fibers 13 mm long with a diameter of 0.175 mm and an aspect ratio (length to diameter) of 74 were used for SFRCM. A thin brass coating is applied to the fibers during their production; however, the coating disappeared during the mixing process. The characterizations of the used steel fibers are also presented in Table 2.

3.2 Mixture proportions and mixing procedure
The mixture proportions for concrete and mortar are summarized in Table 3. One HPC mix (H) and two SFRCM mixes were made for comparison (U1 and U2). The only difference between U1 and U2 was the fiber content to investigate fiber volume effects on the mortar properties. A special mixing procedure was adopted for mixing SFRCM as follows:
- Mixing of dry components (aggregate, cement, and silica fume) for 5 minutes.
- Gradual addition of water to the mixing components for 4 minutes.
- Turning off the mixer for 1 minute.
- Mixing of the mixture for 3 minutes.
- Addition of steel fibers, and mixing for an additional 4 minutes.

The flowability of the fresh SFRCM mortar was evaluated by measuring the mini-slump flow by using the standard procedures given by EFNARC [27]. A truncated cone mold with a diameter of 100 mm at the bottom, 70 mm at the top, and a height of 60 mm was placed on a smooth plate, filled with mortar, and lifted upward. The slump flow deformation was
defined as the dimension of the spread when the mixture stops flowing.

The relative slump flow of SFRCM containing 1% fiber was about 35% showing almost a low fluidity based on Mehdipour et al. [28] research. This should be caused by the steel fibers in the mixtures [29].

### Table 3: Mixture proportions for concrete and mortar samples

<table>
<thead>
<tr>
<th>type</th>
<th>Sample code</th>
<th>Cement (Kg/m³)</th>
<th>Silica Fume (SF) (Kg/m³)</th>
<th>Aggregate (Kg/m³)</th>
<th>SF replacement (% of binder weight)</th>
<th>w/cm</th>
<th>Fiber (% volume)</th>
<th>Super plasticizer (% of binder weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC</td>
<td>H</td>
<td>370</td>
<td>30</td>
<td>1756</td>
<td>7.5</td>
<td>0.36</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>SFRCM</td>
<td>U1</td>
<td>1050</td>
<td>350</td>
<td>698</td>
<td>25</td>
<td>0.16</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>SFRCM</td>
<td>U2</td>
<td>1050</td>
<td>350</td>
<td>620</td>
<td>25</td>
<td>0.16</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

#### 3.3 Casting and curing of concrete specimens

All the tests were performed on three replicates. The average values are used in the discussion of the test results.

HPC samples were vibrated on the table after molding. However, the procedure for SFRCM was different. The fresh SFRCM was poured into the mold in three separate layers, and was compacted 25 times in each layer by a bar for minimizing the trapping of voids. Finally, the molds were vibrated for 45 seconds on a vibrating table.

All the specimens were left covered after casting in a standard lab room for 24 hours, and then the specimens were de-molded and sent for curing. HPC samples were cured in the standard conditions (water curing at 23±1°C) for 28 days. The casted SFRCM samples were placed in a steel water tank and gradually heated until 80°C, the temperature was kept constant for five days; after this period the water temperature was gradually lowered to the lab environment condition over the course of six hours. The procedure minimizes the effect of sudden temperature rise and drop during heating and cooling. This type of curing helps to obtain higher early strengths (favorable for the pre-cast concrete industry), and makes possible some hydration reactions that do not happen in the normal curing [30]. Using a higher temperature is wasting of energy and may cause a lower ultimate strength as mentioned by Yazdani et al. 2008 [31]. However, a separate study is needed to investigate the effect of the curing temperature on hardened SFRCM characterizations.

#### 3.4 Test program

##### 3.4.1 General properties

Common mechanical properties of SFRCMs and HPC including compressive strength, flexural strength, tensile strength, and modulus of elasticity were determined based on BS 1881, ASTM C78, ASTM C496, and ASTM C469 standard methods, respectively. In addition, uniaxial direct tensile test was performed on the dog-bone shaped samples (Fig. 1) to observe the strain-hardening behavior of SFRCM and HPC specimens under direct tension. The loading was applied with a strain rate of 0.00002 per second for this test.
3.4.2 Water absorption
The water absorption test was performed based on ASTM C642 where the 100×100 mm cubic specimens were oven-dried at 105°C for 72 hours. The absorption of each specimen was measured by calculating the increase in mass resulting from immersion of the specimens in water as a percentage of the mass of the dry specimen. The water suction porosity and density of the hardened concrete or mortar were also determined by formulas available in ASTM C642.

3.4.3 Water penetration
The water penetration test was carried out on three replicate 150×150 mm cylinder specimens in accordance with ISO/DIS 7031 (1983) [32]. Samples were subjected to three levels of water pressure of 1, 2, and 7 atm. After breaking the cylinders into two halves through the splitting tensile test, the penetration of water was measured for each sample by a caliper.

3.4.4 Resistance to elevated temperature
Several 50×50×50 mm samples were made for this test. The specimens were oven-dried at 105°C for 5 days, and then heated up to different target temperatures with a nominal heating speed of 5°C per minute. The temperature was kept constant for 2 hours after reaching the target temperature, and then the electronic furnace was turned off to let the specimens cool down gradually over the course of two hours. The weight and residual compressive strength of the cooled specimens were determined.

3.4.5 Thermal expansion coefficient
Measurements of thermal expansion coefficient are usually performed by recording the
linear length change of specimens subjected to different temperatures [33]. This coefficient highly depends on the specimen moisture content in cementitious materials [34].

Performing the test in an oven is an option; however, since air has a lower thermal conductivity compared to water, the temperature distribution in an oven is less uniform than a water bath, and thus using an oven may cause more errors in measurement of the value of thermal expansion coefficient. In other words, the time necessary for reaching a thermal equilibrium would be longer for the test in an oven [35].

In the current work, the thermal expansion coefficient was determined through measuring the length change of 75×75×250 mm prism specimens in a water bath with a variable temperature. The temperature of the water bath was monitored by an accurate digital thermometer. By plotting \( \frac{dL}{L} \) (length change to initial length) versus \( T \) (temperature), and by using the following formula, the thermal expansion coefficient (\( \alpha \)) was calculated for each sample [36].

\[
dL/L = \alpha \cdot dT
\]  

### 3.4.6 Drying shrinkage

The free shrinkage test was performed according to ASTM C157 (2003). The test method involves measuring the length changes of 75×75×250 mm concrete or mortar prisms. The initial length change measurements of the specimens were accomplished after the demolding of specimens by a comparator according to ASTM C490 (2003). Then, the concrete or mortar specimens were cured as described in section 3.3. Finally, the prisms were removed and placed in a controlled environment of 25ºC ± 1ºC and 50% ± 2 RH (relative humidity). The length changes were measured over a period of 60 days, and strains were calculated by dividing the change in length by the initial length.

### 4. RESULTS OF EXPERIMENTS

#### 4.1 Mechanical properties

Some common mechanical properties of the casted materials were measured, and the results are presented in Table 4. A comprehensive study on mechanical properties, particularly uniaxial and triaxial behaviors of these materials was also performed by the authors, and the results are already published elsewhere [6].

The compressive strengths of U1 and U2 were about three times greater than H. The higher strength could be attributed to the lower water to binder (w/b) ratio, more homogeneous bulk by eliminating coarse aggregate, the use of steel fibers, and heat treatment in SFRCM samples. Some less reactive forms of silica exist in SF that do not have pozzolanic reactions under the standard curing. These phases are activated at higher temperatures leading to more pozzolanic reactions during the curing period, and therefore, a higher strength of the concrete or mortar is expected [31].

In addition, the use of higher amount of steel fibers in U2 led to an enhancement in compressive strength up to 10% compared to U1. The same trend was observed in the results of the flexural and tensile strengths. However, the effect of higher fiber volume in U2 was
more noticeable in these two tests. Flexural and tensile strengths of U2 were higher than in U1 by 17% and 19%, respectively.

An obvious difference existed in the modes of the failure in HPC and SFRCM. HPC samples shattered during the tests and had a brittle failure, while SFRCM samples kept their shape until the failure. It implies the higher ductility of SFRCM compared to HPC as the result of the steel fibers incorporation in the mortar. The fibers are able to transfer loads by bridging the cracks because of the strong bond between fibers and mortar [1].

<table>
<thead>
<tr>
<th>Item</th>
<th>Compressive Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>BS-1881</td>
<td>ASTM C78</td>
<td>ASTM C496</td>
<td>ASTM C469</td>
</tr>
<tr>
<td>H</td>
<td>54.6</td>
<td>7.9</td>
<td>3.5</td>
<td>33.8</td>
</tr>
<tr>
<td>U1</td>
<td>149.7</td>
<td>16.4</td>
<td>11.6</td>
<td>42.3</td>
</tr>
<tr>
<td>U2</td>
<td>161.3</td>
<td>19.2</td>
<td>13.8</td>
<td>47.6</td>
</tr>
</tbody>
</table>

*each value is an average of 3 numbers

Fig. 2 also depicts the strain-stress curve for direct tension loaded specimens for assessing the post-cracking tensile response of the materials. As can be seen from the figure, SFRCM exhibited sustained tensile strength after first cracking because of the bridging effect of the fibers. The mortar with higher fiber content tended to have higher tensile strength and energy absorption. The initial parts of all graphs are linear, which implies an elastic behavior. A hardening occurred in both U1 and U2, but it was more considerable in U2 samples because of the higher fiber content. This response continued until reaching first-cracking of the samples where the non-linear behaviors of the materials started. The softening (change in slope or reduction in modulus) started in U1 in a lower stress level compared to U2 because of the difference in the fiber content. The softening started at around 2.5 MPa and 5.5 MPa for U1 and U2 samples, respectively. The HPC samples failed quickly since they had small post-cracking strength; however, the cracking phases of SFRCM samples started after first-cracking point. Both un-cracked and cracked sections contribute to maintain the stress level by crack bridging capability of steel fibers [37]. U2 samples kept their stress levels and underwent strain more than U1 samples since they had more fibers to connect the cracks.

The distance between the initial points of cracking and crack widening phases (crack saturation point) in U2 was almost 2.6 times greater than U1. The samples became saturated by cracks after experiencing them repeatedly until the widening phase started. The widening of cracks and pulling fibers out of the cementitious matrix occurred while stress level went down continuously until final failure of the samples. Stress level decrease with a higher rate in U2 samples compared to U1. In other words, U2 samples lost their strength after the crack saturation point faster than U1 samples. This trend could be attributed to the weaker matrix of U2 after fiber pull out.

If the point of the crack widening initiation is considered a failure point, then, U1 was able to tolerate 6.3 times more deformation until its failure in comparison to HPC. The strain borne by U2 samples was also 10.9 and 1.7 times greater than H and U1 samples,
respectively. This implies the superior capabilities of SFRCM to deform substantially (compared to normal and high performance concretes) before the failure, however, these values are still far from the normal steel capacity for the deformation under axial load.

The calculated values for tensile strength in the direct tension test were less than those obtained in ASTM C496 standard method. The reason is attributed to some assumptions in the standard method, which are not in accordance with strain-hardening behavior of fiber reinforced materials like SFRCM.

SFRCM compressive modulus of elasticity (E) values for U1 and U2 were higher than HPC by about 25% and 41%, respectively. However, the ratio of E in SFRCM to E in HPC was not as high as other test results of this section. The higher fiber content in U2 caused a higher amount of E value in these samples by 13% compared to U1 samples. The explanation for that could be the higher steel fiber content in U2, because steel has a greater modulus of elasticity than mortar (Modulus of elasticity in steel is about 200 GPa [38]).

Figure 2. Strain-Strain curve of samples in direct tension test

4.2 Water absorption
This test was performed according to ASTM C642 on HPC and SFRCM samples and the results are shown in Fig. 3 (three specimens for each test). Moreover, the density and water suction porosity were calculated by using the standard code formulas, and the results are included in the figure as well.

The low porosity of SFRCM could be deduced from water absorption and water suction porosity test results. The porosity of concrete and mortar impacts both strength and durability. The average water absorption in HPC samples was more than four times greater than U2. The water suction porosity in SFRCM samples was about three times less than in HPC samples as well. The water absorption and water suction porosity of U1 samples were
greater than U2 samples by about 0.3% and 1%. This difference may be due to the fact that steel cannot suck high amount of water. Therefore, less water absorption for a sample with a higher steel fiber content was expected. However, more steel fiber content can also increase the porosity because of the Interfacial Transition Zone (ITZ) around the fibers, and the lower workability of mortar with higher steel fiber content.

The water absorption values of HPC samples were also low compared to some reported values of other researchers, and they satisfied the durability criteria of some standard codes [3,39-41]. Therefore, SFRCM that had even a lower absorption can have much potential for great durability performance.

SFRCM had also higher densities compared to HPC samples (Fig. 3-c); the densities of U1 and U2 were higher than H by 6% and 11%, respectively. This indicates a denser structure of SFRCM and the influence of steel fibers on the density. The incorporation of more steel fiber in SFRCM increased the density of the material. The density went up by using a higher volume fraction of steel fiber in U2, because steel has a higher specific density than the other mixing components. In addition, according to the water absorption and suction porosity measurements, the porosity of U2 was less than in U1 samples. The lower porosity was another factor that contributed to the higher density of U2 in comparison with U1.

All these tests confirmed the fact of the dense structure of SFRCM samples, compared to normal and high performance concrete.

![Figure 3. Water absorption, void content (%), and density in HPC and SFRCM samples](image)

4.3 Water penetration

Fig. 4 demonstrates the results of the water penetration test according to ISO/DIS 7031 (each value is an average of three test results). According to the results, water could penetrate into SFRCM more slowly compared to HPC. Water could penetrate into H more than 3 times easier when compared to U1. It is in accordance with the test results in the previous section. However, it seems that the penetration in SFRCM was mostly due to the fiber existence; otherwise, considerably lower penetration (even near zero) was expected in the mortar without fiber. As can be seen in Fig. 4, the depth of penetration increased by 30% with 1% increase in the amount of fiber in U2. ITZ around the fibers provides a way for penetration of water or other deleterious agents into the material. The higher fiber content means that it is easier for water to find a path to penetrate inside the sample under the test
pressure. However, other super properties of SFRCM like low absorption and void content could compensate this weakness to some extent.

Figure 4. Results of water penetration test (mm)

4.4 Resistance to elevated temperature
The performance of materials exposed to elevated temperatures is one of the most important topics in concrete research. A common method for investigation of materials behavior exposed to elevated temperatures is monitoring the weight loss of material during the heating procedure. Fig. 5 illustrates the weight loss of oven-dried specimens after their exposure to the elevated temperatures (each value is an average of three test results). The major weight loss is attributed to the dehydration of several hydrates, the dehydroxylation of portlandite, and the decarbonation of calcium carbonate [42].

The weight loss of SFRCM specimens was about twice of HPC samples. Considering the water to binder ratios (0.36 for HPC, 0.16 for SFRCM) and binder contents of HPC and SFRCM (400 kg/m$^3$, 1400 kg/m$^3$, respectively), it has been concluded that the amount of mixing water percentages were 6.0% and 9.3% of the weight of the material for HPC and SFRCM, respectively; thus, more weight loss induced from evaporation of mixing water was expected for SFRCM samples. However, the ratio of the mixing water in HPC to SFRCM ($6/9.3=0.64$) was less than the ratio of the weight loss induced from in HPC to SFRCM at 600°C ($0.58$). It seems that by elevating the temperature, the existing gel and chemical combined water in SFRCM release easier than those of HPC samples. It is reported that in the temperature range of 100°C to 250°C, the loss of water from the C-S-H gel and aluminate hydration products such as ettringite is the main cause of the weight loss [43]. As a result, SFRCM which contained more C-S-H was expected to have a higher weight loss compared to HPC from this point of view. The lower weight loss in HPC samples is also attributed to the higher aggregate content of HPC samples in comparison with SFRCM.
(Table 3). Since the specimens were oven-dried, therefore, a low amount of water was expected to be left in the samples’ aggregate after the drying process at 105°C. Thus, HPC with the aggregate mass more than twice of that in SFRCM showed less weight loss.

The slope of the graph at the higher temperatures was less due to the different mechanisms of the weight loss. In other words, the samples lost their weight at a slower rate at the higher temperatures. In the lower temperature ranges, the weight loss is due mainly to the evaporation of the free water present in the voids and capillary pores. In the high temperature ranges, the weight loss comes from the adsorbed water in smaller pores and chemically bound water.

Spalling is another unfavorable phenomenon that may happen at elevated temperatures. The spalling is caused by extremely high water vapor pressure generated during the heating and thermal stress [43]. The moisture content influences the extent of spalling. Higher humidity levels lead to a greater spalling.

![Weight loss of specimens by elevation of temperature](image)

Figure 5. Weight loss of specimens by elevation of temperature

Fig. 6 shows explosive spalling of U1 and U2 after their exposure to 600°C when specimens were not oven-dried. These samples did not undergo the drying process in an oven as described in section 3.4.4. HPC samples that were not oven-dried broke into so many small pieces during the heating procedure. Thus, all the samples were oven-dried to eliminate the effect of different moisture contents on the test results.
Fig. 7 shows the ratio of the residual compressive strength (Cs) to the initial strength (C) (at lab environment condition) at different temperatures. The compressive strength increased with the temperature elevation to 300°C and then a drop was observed in all the specimens. The maximum achieved strength was at about 300°C, and the compressive strength of U2 reached about 206 MPa at 300°C. The increase in the strength could be attributed to a rehydration of the paste due to the migration of water in the pores to form a new gel, the hydration of unhydrated particles, which were activated as a result of the higher temperature, the formation of strong chains of C-S-H which is the most important phase in hardened paste, and the increase in the forces between gel particles (van der Walls forces) due to the removal of water [44-46]. The increase in the strength in H was greater than in U samples (60% for H versus 20% for U1). This might be mainly due to more available water for unhydrated cement particles in HPC samples. A high amount of cementitious material (1400 kg/m³) in SFRCM sample led to the consumption of a considerable portion of the mixing water. In addition, SFRCM with a lower porosity is more prone to micro-crack formation under elevated temperatures than HPC. The strength loss at the elevated temperature was due to the decomposition of the cement hydration products, the weakness of the bond between cement paste and aggregate, and the formation of micro-cracks in the paste [47].

Fig. 8 illustrates visual condition of the oven-dried specimens after their exposure to the temperature of 600°C. The formation of fewer cracks in HPC samples implies a better performance of these samples compared to SFRCM from this point of view. The higher permeability of HPC must be the main cause of this phenomenon. Visible cracks started to be formed at 400°C in all the samples. It is noted that the crack occurrence is mainly due to the thermal incompatibility between the cement paste and the aggregates.

U1 experienced a spalling in the process of heating; however, U2 with the higher fiber content showed only a few micro cracks on the surface. In fact, the fibers in SFRCM specimens were beneficial during the exposure to the elevated temperature by keeping the cementitious matrix away from spalling.

In addition, U1 samples were more homogeneous than U2, regarding the lower volume of steel fiber in U1. Thus, a greater level of sensitivity to thermally induced defects due to the more homogeneous microstructure was predicted as well.
Figure 7. Relation between ratio of residual strength to initial strength at different temperatures

Figure 8. Visual inspection of oven dried specimens at 600 °C
4.5 Thermal expansion coefficient

Linear thermal expansion coefficients ($\alpha$) (from 0°C to 70°C) of HPC and SFRCM samples were measured, and the results are presented in Fig. 9. The slope of plotted line is $\alpha$ for each specimen set.

The values of $\alpha$ in SFRCM were higher than HPC samples. It is reported that by increasing the porosity of the concrete, $\alpha$ would decrease [48]. By regarding the dense matrix, higher cement paste volume, and fine aggregates in SFRCM, this outcome was expected. Moreover, the thermal expansion coefficient values for aggregates are usually smaller than those of cement paste [49]. Therefore, HPC with lower aggregate content (Table 3) should have a lower thermal expansion coefficient than SFRCM. The most commonly used value in design of normal concrete structures is about 11 micro-strain/°C [50]. Therefore, SFRCM deforms up to 40% more than normal concrete under a temperature gradient. This problem can be resolved by using some strategies in structure design like the placement of necessary joints.

Wyrzykowski et al. [34] observed an increase in the thermal expansion coefficient with a decrease in the internal relative humidity (RH). Since the specimens were submerged in water during the test, and by assuming the samples mature at the time of testing, RH could not substantially affect the value of thermal expansion coefficient. In addition, penetration of water into the specimens, particularly for SFRCMs is difficult during the test. The water penetration test revealed a low permeability level of SFRCMs as well as of HPC samples.

SFRCM which contained a higher volume of steel fibers (U2) exhibited a higher value of $\alpha$. In fact, after putting more fibers in SFRCM, the porosity went down. This conclusion could be drawn from water absorption and porosity determination tests as well.

Figure 9. Variation in lengths of specimens in different temperatures
4.6 Drying shrinkage

Since shrinkage is the major cause of the cracking in concrete and mortar, it should be carefully monitored. The cracking due to shrinkage can reduce the performance of structures, especially in corrosive environments. The cracks can create a direct path for penetration of the aggressive ions into the concrete, and endanger the durability performance. Thus, in order to perform a proper design of structures, the deformation behavior of materials should also be considered [51].

Fig. 10 shows the deformation of the specimens due to drying shrinkage in different ages. SFRCM mixes which underwent a heat treatment exhibited a large unrestrained shrinkage strain at early ages. This high rate of shrinkage soon dropped off, and a negligible length change was observed at a later time point. In fact, there was a difference between the shrinkage behavior of SFRCM and HPC as well as normal concrete.

Shrinkage is caused by the loss of water due to the evaporation or chemical change occurred in hydration of cement. In fact, the shrinkage of concrete and cementitious mortar is believed to take place in the cement paste matrix.

The total shrinkage of SFRCM samples was higher at early ages most probably due to the larger autogenous shrinkage in their mixtures. The main reasons are the low water to binder ratio and high amount of cementitious materials in SFRCM. A high autogenous shrinkage is expected when the heat treatment is applied; this shrinkage is completed at the end of the treatment. This kind of shrinkage exists in HPC samples as well [52]; however, it was considerably smaller than the shrinkage in SFRCM. The total shrinkage values after 3 days in U1 and U2 samples were 7.8 and 6.7 times, respectively, greater than in H samples.

The high amounts of cement and SF content could be other reasons for the high value of the shrinkage deformation at the early ages in SFRCM specimens. In fact, due to the reduction of aggregate/binder ratio, the skeleton supposed to resist shrinkage is also reduced.

The slopes (rates) of shrinkage in both types of SFRCM samples at their early ages were almost the same; because the mortar mixtures of both materials were similar, and the shrinkage occurred primarily in the cementitious matrix. However, by comparing the ultimate shrinkage values of U1 and U2, the specimens with the higher fiber content (U2) yielded less shrinkage than the other one. The total free shrinkage in U2 was about 85% of U1 after 60 days.
5. DISCUSSION

The construction of structures using steel fiber reinforced cementitious mortars could improve their service life with minimal maintenance requirements. Based on mechanical, durability, and dimensional stability test results, SFRCM seems to be a promising material in the construction of bridges, offshore structures, pre-stressed concrete, etc.

The material properties must be precisely determined before making reliable models for design of costly structures. The use of some available formulas which relate uniaxial compressive strength to the different mechanical properties of concrete such as modulus of elasticity and tensile strength is a common procedure among structure designers. However, these formulas could not always be reliable, particularly for special materials like SFRCM.

This fact necessitates an in-depth study on different properties of composite materials like SFRCM. Investigation of the uniaxial and triaxial behaviors of SFRCM and comparison with HPC was another part of the current study, and the results are already published in another paper [6].

Based on the results of water absorption, water suction porosity, and water penetration tests, the low porosity, permeability, and hence exceptional durability performance are expected from SFRCM. If the porosity is high and the pores are interconnected, they contribute to the transport of fluids or gases through the concrete or mortar. However, the permeability is not a simple function of porosity, but also depends on the size, distribution, shape, and continuity of the pores.

It is also noteworthy that the difference between densities in SFRCM and HPC mixes was less than 10%. Thus, SFRCM, with almost the same unit weight as other common concrete mixtures, has a superior performance which could be compared even with steel.
Therefore, the material applies less dead load compared to the steel elements of the same shape. However, other structural design considerations like bucking should be taken into account as well.

The behavior of SFRCM subjected to elevated temperature was also different from HPC. The rate of increase or drop in compressive strength was faster in HPC specimens compared to SFRCM. In other words, strength of HPC was more sensitive to the temperature changes compared to SFRCM. More available water in HPC pores could be a reason; the water could be used in rehydration process during heating. In addition, by considering the higher porosity of HPC, the crack occurrence during the heating procedure was more likely for SFRCM. As a result, a higher level of strength loss was expected in SFRCM.

The presence of steel fibers enhances tensile strength and deformation capacity of the material. Fibers also bridge the cracks caused by the internal pressure in the concrete leading to a decrease in risk of spalling [53]. Some studies have shown that by the addition of polypropylene fibers, spalling in concrete under elevated temperatures could be minimized [54]. Therefore, the effect of polypropylene fibers in properties of SFRCM could be studied for structures with possible elevated temperatures issues.

Thermal expansion and drying shrinkage were different in SFRCM samples as well. These kind of deformations is caused by changes in temperature and moisture of the material [55]. The amount of thermal expansion coefficient values (α) in HPC and SFRCM were more than normal concrete. A higher α may affect the durability problem because of micro-cracking at the paste-aggregate interface [55]. Moreover, this fact must be considered in practice, especially in design of expansion joints to control the external restraints and modelling the thermal behavior of the material. SFRCM tends to deform more than normal and high performance concrete under temperature changes. It is also very important to consider this fact in steel bar reinforced SFRCM; because incompatible deformation between steel bar and mortar under a temperature gradient may cause internal cracking.

There is a difference between the shrinkage behavior of SFRCM and HPC as well as normal concrete. These different shrinkage behaviors must be considered by precast and cast-in-place concrete manufacturers for successful casting of SFRCM; they must try to mitigate or eliminate restraints on the members for prevention of the crack occurrence.

6. SUMMARY AND CONCLUSIONS

The paper investigates the results of some mechanical, durability, and dimensional stability tests performed on a special steel fiber reinforced cementitious mortar (SFRCM) with two different fiber contents. The performance of the mortars was compared with a common type of high performance concrete (HPC). On the basis of the results obtained in the experimental investigation, it can be concluded that:

- Mechanical characteristics of SFRCM were considerably better than HPC. The compressive, flexural, and tensile strengths in U2 samples were 2.95, 2.43, and 3.94, times greater than in H samples, respectively. In case of tensile and flexural strengths, the addition of higher volume of steel fiber remarkably increased the strength and energy absorption.
Low water absorption and water suction porosity of SFRCM revealed a dense structure of this material. The water absorption and suction porosity of U2 samples were about 4 and 3 times less than in H samples, respectively.

- The density of SFRCM was almost equal to other normal concretes and mortars. Thus, the mortar has an exceptional performance with almost the same unit weight compared to other types of common concrete and mortar.
- Fiber might provide a path for transportation of liquids or gas in the mortars.
- The higher porosity of HPC caused a better performance at the elevated temperatures in comparison with SFRCM.
- Thermal expansion coefficient in SFRCM was higher than HPC by 15% and 19% for U1 and U2, respectively.
- Shrinkage behavior of SFRCM was different from other types of common concrete and mortar. It seems that the most important reason could be the curing procedure of SFRCM.
- SFRCM seems to be a promising material for construction of special structures such as bridges, marine structures, skyscrapers, etc.

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