Article

Effect of Exposure to High Temperature on the Mechanical Properties of SIFRCCs

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Abstract: Many researchers have studied explosion prevention and fire resistance of high-strength concrete mixed with organic fiber and steel fibers. The fire resistance of high-performance fiber reinforced cement composites is desirable in terms of physical and mechanical properties. However, the use of a polymer as an alternative to organic fiber has not been clearly studied. In this study, a slurry infiltration method was used to obtain slurry-infiltrated fiber-reinforced cementitious composites (SIFRCCs) specimens. Powder polymer was used instead of organic fibers during mixing of the slurry. The compressive and flexural strengths of the specimens after 1 hr of high temperature exposure according to the KS F 2257 (ISO 834) standard fire-temperature curve were measured. The addition of the polymer before and after high temperature (about 945 °C) exposure affected the strength of the SIFRCCs. The compressive and flexural strengths were decreased after exposure to high temperature in comparison with SIFRCCs without polymer because polymer create capillary pores due to melting and burning when exposure to high temperature. This minimizes the vapor pressure inside the concrete model and reduces the failure of the concrete model. The experimental results showed that the flexural strength at a high temperature for 1.0 % polymer content was the highest at 53.8 MPa. The flexural strength was reduced by 40~50% when compared to the flexural strength before high temperature exposure and comparing to SIFRCCs without polymer, the compressive strength in 1.5% polymer is lower, owing to voids that are created in the SIFRCCs after exposure to a high temperature.

Keywords: slurry-infiltrated fiber-reinforced cementitious composites (SIFRCCs); high temperature exposure; fire resistance; compressive and flexural strength; powder polymer

1. Introduction

Concrete is an economical construction material that has been used for a long time in buildings and other infrastructures in modern society. Concrete is an inert material with better performance at high temperature exposure than that of other construction materials, such as timber and steel, owing to its non-combustibility and low thermal conductivity [1]. However, various problems have been observed in conventional concrete, such as low strength and brittle fracture behavior. High-performance fiber reinforced cemented composites (HPFRCs) can be used to provide high compressive strength and ductile behavior to address these problems. Structures are increasing in size with a wide usage range because of the rapid development of construction technology. The functions of the structures are also becoming more complex. The explosion and fire factors are increasing each day. [2]. Recently, HPFRCs have been evaluated to improve the impact and explosion functions in preparation for unexpected terrorism and explosion accidents. HPFRCs are generally susceptible to severe damage under fire conditions [3,4]. Steel fiber can support the structure of concrete at
elevated temperatures due to a high melting point [5,6]. The engineered cementitious composite (ECC) material is based on polymeric fibers, e.g., polypropylene (PP) and polyvinyl alcohol (PVA) fibers. The vapor pressure that formed by fire can be effectively relieved and, consequently, ECC shows better spalling resistance than that of plain mortar [7,8]. ECC has improved fire resistance due to the use of polymeric fibers, such as polyvinyl alcohol (PVA) fibers, which can melt and create channels for alleviating internal vapor pressure, thus preventing explosive spalling [6–9]. Numerous studies have evaluated the residual mechanical properties of HPFRCCs, i.e., slurry-infiltrated fiber-reinforced concrete (SIFCON), ultra-high-performance fiber-reinforced concrete (UHPFRC), etc., which were exposed to an elevated temperature [3,4,7,10–13]. Post-fire pull-out tests of steel bars that were embedded in HPFRCC showed that the use of HPFRCC enhanced the bond strength [14]. Steel fibers approximately doubled the toughness of the unheated concrete. The fibers were effective in reducing the degradation of compressive strength of the concrete after exposure to the elevated temperatures. The steel fiber reinforced concretes also had the highest toughness values after high-temperature exposures [15]. The degradation of mechanical performances of BFRP laminated structural due to high temperature is because of the decomposition of the epoxy resin matrix with increasing temperatures. Internal de-bonding occurs in the fibers due to the weak adhesion of epoxy resin matrix at a high temperature [16]. Slurry-infiltrated fiber-reinforced cementitious composites (SIFRCCs) and HPFRCCs in the form of SIFCON were developed to provide sufficient energy absorption capacity and excellent resistance against unexpected impacts and explosions. SIFRCCs improve tensile resistance and crack propagation after maximum load, owing to the high volume of steel fiber. The high volume fraction of steel fiber in SIFRCCs provided high direct tensile strength, compressive strength, and improved brittleness [17]. The flexural strength decreases as the exposure temperature increases, owing to the loss of water and the strength of the slurry matrix [18]. However, the absence of capillary pores in SIFRCCs makes it more susceptible to explosive spalling. The vapor pressure increase and non-uniform increase in temperature cause the explosive spalling of the SIFRCCs at a high temperature. Polymer mix concrete is a new material emerging in the construction industry. The presence of the polymer introduces a considerable improvement in the ductility of the material, drastically reducing the surface cracking, which is prerequisite for increasing the durability and for reducing stiffness damage [19]. A reduction in the w/c ratio in PVA-added mixtures should result in an increase of the compressive strength of the composite material [19]. Many researchers have evaluated the physical and mechanical properties of polymer mix concrete [6–8,13,19]. The addition of steel fibers can change failure mode and improve ductility. The cracks are smaller in width and greater in number with increasing steel fiber content. The steel fiber improved the residual compressive strength and ductility of self-compacting high performance concrete subjected to high temperatures, but steel fiber did not mitigate the spalling of concrete [20]. The polymer powder with a melting point of 120 °C forms pores during melting at a high temperature, which lowers the internal water vapor pressure and minimizes structural failure, owing to explosion, impact, and fire. HPFRCC is vulnerable to explosion in the event of fire, owing to its impact and explosion resistance through the interaction and ductile behavior of the steel fibers. The main objective of this paper is to provide experimental data on the polymer mix SIFRCCs, compression, and bending test were performed to examine the effect of high temperature on compressive and flexural strength of specimens. High water pressure might arise when exposed to fire due to the high density of SIFRCCs. This can contribute to degradation of the concrete structure. Polymer powder was used and it helps to create capillary pores due to melting and burning when exposure to high temperature to overcome this problem. Moreover, around the fibers, passes zones to the cement matrix were formed. From this existing passes zones between fine aggregates and matrix are interlinked, so that permeability increases and the steam pressure is reduced. Therefore, this study evaluated the mechanical properties of SIFRCCs before and after exposure to a high temperature using polymer powder, in replacement of organic fiber.
2. Materials and Methods

2.1. Used Materials

Ordinary Portland cement (OPC) type I was used in this study [18,19,21]. To obtain the desirable flexural strength, silica fume, with a size of 0.3 mm to 1.0 mm, fine aggregate (FA) was used [17,21]. No coarse aggregate was used to improve the filling performance of the slurry. A polycarboxylic acid high range water reducer (HRWR) was used to improve the filling performance. The HRWR was highly distributed to manufacture high-strength concrete. A shrinkage reducing agent (SRA) that was mainly composed of organic surfactants and glycol ether was used to reduce the shrinkage stress of the cementitious composite and cracks in the dry concrete. In this study, hooked-end steel fibers were used with aspect ratios of 80, as shown in Figure 1 (diameter of 0.75 mm, length of 60 mm). The tensile strength of the steel fibers was 1200 MPa [22]. Polymer powder with a particle size of 0.1 μm to 5 μm was used [23]. Figure 2 shows used polymer powder.

2.2. Mixing and Fabrication of the Specimens

The water-binder ratio was fixed to 0.35 to obtain the filling performance of the high-performance slurry for filling the inner space of the steel fibers that were placed in advance to mix the SIFRCCs. SIFRCCs are a type of HPFRCC that can contain a high volume of steel fibers. It is fabricated by dispersing the steel fibers and then filling the high-performance slurry. SIFRCCs prevent the fiber ball phenomenon and allow for a high fiber volume fraction [2,20,24,25]. The amount of polymer powder added during slurry mixing was 0%, 0.5%, 1.0%, and 1.5%. The silica fume was added at 15% of the cement weight. The fiber volume fraction variables were set to 5%. The cement and aggregate ratio was 1:0.5, and percent of Shrinkage Reducing Agent (SRA) was 0.05% of the binder. Table 1 lists the mixing ratio of the specimen. First, the cylindrical mold, with a diameter of 100 mm and height of 200 mm, and prismatic specimens of 100 mm × 100 mm × 350 mm, were filled with steel fiber and then filled with the prepared slurry to test the compressive strength and flexural strength, respectively.
was conducted with only one side exposed to the high temperature using fire resistance fiber cerawool.

were fabricated to evaluate the compressive and flexural performance of the polymer SIFRCCs with ASTM C 1609 and ASTM C39, respectively [26–27]. Figure 3 shows the compressive test and flexural strength test set up using a 200-ton universal testing machine that was provided by Dong Ah Testing Machine. In addition, the deflection displacement at the center was measured, in which two linear variable differential transducers (gauge length 25mm) were attached. The load was applied at the rate of 1 mm/min. in the displacement control method for both compressive and flexural test. Ten specimens for each variable were tested. In addition, for compressive strength, the specimens were centrally placed between the two compression plates, such that the center of the moving head was above the center of the specimen. Subsequently, the load was applied on the specimens by moving the movable head. The load and corresponding contraction were measured at different intervals. Previous studies on the mechanical properties of high-strength concrete and fiber-reinforced concrete showed that there was an applicable strength limit for each prediction equation [28–34]. Equation 1 was utilized to calculate the flexural strength.

\[ f = \frac{PL}{bd^2} \]  

(1)

**Figure 3.** Experimental set up for the specimen before high temperature exposure: (a) Experimental set up for the compressive strength test before high temperature exposure; and, (b) Experimental set up for the bending test with third point loading before high temperature exposure.

Here, \( f \) is the flexural strength; \( P \) is the maximum load measured in the experiment; \( L \) is the span distance (300 mm); \( b \) is the specimen width (100 mm); and, \( d \) is the specimen height (100 mm).

The specimen was heated for 1 hr in accordance with the KS F 2257 (ISO 834) standardized material temperature curve in a high temperature furnace to analyze the flexural and compressive strengths of the polymer-containing SIFRCCs subjected to a high temperature (about 945 °C) [35]. The experiment was conducted with only one side exposed to the high temperature using fire resistance fiber cerawool. The average temperature inside the high temperature furnace was adjusted according to equation

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**Table 1. Mix proportion ratio.**

| W/B | OPC | Silica Fume | Polymer (\( V_p \), %) | FA | HRWR | SRA | Steel Fiber (\( V_f \), %) |
|-----|-----|-------------|------------------------|----|------|-----|------------------------|
| 0.35 | 1   | 0.15        | 0                      | 0.5| 0.025| 0.005| 5                      |

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When compared to 0% polymer SIFRCCs, the compressive strength in 1.5% polymer is lower, owing to voids created in the SIFRCCs after exposure to a high temperature. The compressive strength decreased was significant after exposure to high temperature in comparison with SIFRCCs and moisture passes through the created pores. This creates channels to alleviate internal vapor pressure inside the concrete, thus preventing explosive spalling and reduces the failure of the concrete model. Moreover, polymer added mixture should result in an increase of the compressive strength of SIFRCCs before exposure to high temperature, but the increased difference in compressive strength is moderate.

\[
T = 345\log_{10}(8t + 1) + 20
\]

Here, \( T \) is the average temperature in degree Celsius inside the furnace and \( t \) represent time in minutes.

3. Results and Discussion

3.1. Compressive Strength

Figure 6 shows the compressive strength test results before and after high temperature exposure of the steel fiber reinforced cement composites with polymer (%). The maximum compressive strength was 37.2 MPa with 0.5% polymer after high temperature exposure, and a lower value was observed at 1.5% polymer as compared to that at 0% polymer. A high percentage of polymer added during mixing affects the compressive strength after high temperature exposure, owing to an increase in voids. When compared to 0% polymer SIFRCCs, the compressive strength in 1.5% polymer is lower, owing to voids created in the SIFRCCs after exposure to a high temperature. The weight loss of the SIFRCCs owing to the high temperature may decrease the compressive strength [18]. A comparative analysis of the compressive strength characteristics by polymer incorporation rate after high temperature exposure showed that the compressive strength was higher at 0.5% polymer than at 0%, but the compressive strength of other specimen decreases after exposure to high temperature. The steel fibers were effective in reducing the degradation of compressive strength of the concrete after exposure to the high temperatures [15]. The compressive strength decreased was significant after exposure to high temperature in comparison with SIFRCCs without polymer, because the polymer that melts during

**Figure 4.** Time–temperature curve of the KS F 2257 (ISO 834) standard [35].

**Figure 5.** Specimen after exposure to high temperature.
high temperature exposure create voids and moisture passes through the created pores. This creates channels to alleviate internal vapor pressure inside the concrete, thus preventing explosive spalling and reduces the failure of the concrete model. Moreover, polymer added mixture should result in an increase of the compressive strength of SIFRCCs before exposure to high temperature, but the increased difference in compressive strength is moderate.

![Figure 6. Compressive strength before and after high temperature exposure with polymer content (%).](image)

### 3.2. Flexural Strength and Flexural Toughness

Figure 7 shows the flexural strength test results before and after high temperature exposure of the steel fiber reinforced cement composites with polymer. The flexural strength at 1.0% polymer contained the highest strength of 53.8 MPa, and the flexural strength at 0.5% was 47.0 MPa. The flexural strength at 1.5% was 49.1 MPa before high temperature exposure. The bending strength change level with respect to the polymer content was insignificant when compared with 0% polymer content. Thus, the flexural strength was reduced by 40~50% compared to the flexural strength before high temperature exposure, and the flexural strength was superior to that of general concrete. The resistance against bending is improved, owing to high mixing of the steel fibers. At 1.0% polymer contain the flexural strength was 26.3 MPa, whereas at 1.5% was 21.8 MPa after exposure to high temperature. Figure 7 shows a decreased in flexural strength of SIFRCCs after exposure to high temperatures. Increasing the polymer can increase the flexural strength of SIFRCCs after exposure to high temperature. The steel fibers were effective in reducing the degradation of flexural strength of the concrete after exposure to the high temperatures. After exposure to high temperature, the flexural behavior decreases in flexural strength due to the interaction of the high-mixed steel fibers and polymer in the cement mortar. There is a greater chance of decreasing the strength of concrete if exposed to high temperature because of the passing of free water through pores created by the melting of polymer.

Figure 8 shows the flexural toughness test results before and after high temperature exposure. A large energy absorption capacity of 1553 N·m is observed for 1.0% polymer content before high temperature exposure. This is because the high-strength steel fiber of SIFRCCs transfers to the crack surface and, thus, the toughness and energy absorption capacity are increased by absorbing energy through the process of degrading adhesion or drawing out the steel fiber. The flexural toughness test after high temperature exposure showed approximately 50% lower flexural toughness than that before high temperature exposure. When compared to 0% polymer content, the decrease in flexural toughness after high temperature is minimal; however, at 1.5% polymer content, there is a larger difference than that with other variables, because more voids are created on the specimen, owing to the high temperature [18]. From Figure 8, the toughness was 697 N·m when 1.0% polymer was added.
during mixing, whereas 645 N.m at 1.5% was found after exposure to high temperature. Figure 8 shows a decrease in the toughness of SIFRCCs after exposure to high temperatures.

![Flexural strength of the specimen before and after high temperature exposure with polymer content (%).](image)

**Figure 7.** Flexural strength of the specimen before and after high temperature exposure with polymer content (%).

![Flexural toughness of the specimen before and after high temperature exposure with polymer content (%).](image)

**Figure 8.** Flexural toughness of the specimen before and after high temperature exposure with polymer content (%).

The SIFRCCs exposed to high temperature the water inside the element will evaporate and a part of it will flow out of the SIFRCCs. Other part will flow inside the porous medium, depending on the permeability of the materials. SIFRCCs lose more strength if moisture is not permitted to escape when exposure to high temperature due to the increase in internal vapor pressure. The addition of polymer improved spalling, which can melt during high temperature and create channels to alleviate internal vapor pressure.

4. Conclusions

This study analyzed the flexural and compressive behavior of steel fiber reinforced cement composites with polymer (%) that was exposed to a high temperature for 1 hr based on KS F 2257 (ISO 834) standard temperature curve. The results are as follows.

i. The experimental results showed that the flexural strength at a high temperature for 1.0% polymer content was the highest at 53.8 MPa, and the resistance to bending was desirable. The average flexural strength at 0.5% was 47.5 MPa and the flexural strength at 1.5% was
49.1 MPa. When compared to 0% polymer content, the flexural strength did not have more difference that with varying content.

ii. A comparative analysis of the compressive strength characteristics by polymer incorporation rate after high temperature exposure showed that the compressive strength was higher at 0.5% polymer than that at 0%.

iii. The experimental results showed that the flexural strength decreased by approximately 40% to 50% when compared to the bending strength before high-temperature exposure. The voids that were formed by melting the polymer reduced the internal water vapor pressure and strength, owing to the chemical reaction of the cement mortar at the high temperature.

iv. After high temperature exposure, the flexural strength of conventional SIFRCCs and the polymer contain SIFRCCs was measured, which showed a decrease in flexural strength due to the interaction of the high-mixed steel fibers and polymer in the cement mortar. A greater chance of decreasing the strength of concrete existed if exposed to high temperature because of the passes of free water through pores created by melting of polymer.

v. The adding up to 1.5% of polymer powder can reduce the failure rate of the SIFRCCs structure, owing to an unexpected load, such as fire and explosion.

vi. Increasing the amount of polymer decreases the compressive and flexural strength of SIFRCCs after exposure to high temperatures, because the polymer creates capillary pores due to melting and burning when exposed to high temperature.

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