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Abstract. Civil construction faces an immense challenge due to the damages caused by fire during the construction and service phases. Therefore, it is important to study fire being one of the most severe environmental conditions affecting structures in order to mitigate its effects. Moreover, fiber has been generally discovered to be effective as a reinforced material to improve the strength of concretes. This research was conducted to analyze the residual strength of concretes reinforced with aluminum fibers when exposed to high temperatures. This involved the preparation of 25 MPa concrete specimens with the addition of 0.2% fiber contents exposed to 400 °C and 800 °C temperature for 30 minutes after which their compressive and split cylinder strengths were measured. The result showed the fiber increased the compressive strength by 14.37%, 14.90%, and 2.00%, and the split cylinder strength by 47.27%, 44.29%, and 32.09% at 25°C, 400°C, and 800°C respectively in comparison with the normal concrete.

INTRODUCTION

In the development of sustainable concrete, waste has been tried to use in several studies. For example, Atmajayanti *et al.* [1] found the substitution of 50% and 100% of concrete surface treatment by recycled coarse aggregate to have improved the mechanical properties 2.46% and 2.38% of compressive strength, 2.59% and 8.25% of split tensile strength, and 13.14% and 0.69% of modulus elasticity, respectively. Haryanto *et al.* [2] also replaced the aggregates in concretes with tire rubber waste and was found to be efficient at less than 40% content replacement. Moreover, concrete with artificial lightweight aggregate was observed would increase 17.22% of compressive strength by adding carpet waste fiber of 0.44% and 75.18% of tensile strength on a 0.85% fraction of fiber [3]. Various porcelain ceramics

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materials are quite resistant to heat and the wastes have also been used as aggregate for concrete [4-6]. Keshavarz and Mostofinejad [7] investigated coarse aggregate from crushed porcelain waste in concrete resulting in the compressive strength exposed to a temperature of 850 °C was by 20% higher than that of specimens containing normal aggregates.

Aluminum is a lightweight and anticorrosive material applied in several sectors including transportation, electrical, construction, and product packaging and its consumption has been projected to be increased to 120 million tons in 2025 in comparison with the 4.6 million tons recorded in 2006. This means a significant level of waste is expected to be generated without compensating for re-use or re-cycling [8]. Meanwhile, the aluminum waste has been used by Sabapathy *et al.* [9] as fiber through manual production with a loop at both ends, and it was observed to have increased splitting tensile strength of M40, M30, and M20 of concrete grades by 19.19%, 20.92%, and 36.88% respectively at 2% fraction of the fiber. Another study by Haryanto *et al.* [10] concluded that the addition of a 0.3% fraction of fiber waste soda as the optimum volume caused the highest improvement in the concrete's tensile strength by 61.00%. Moreover, the geometry, type, strength, and aspect ratio of fiber have also been developed to be used in reinforcing concrete [11].

The characteristics of fiber have the ability to change the properties of concrete when exposed to heat [12-14] and the reduction of the concrete strength due to physicochemical reactions such as evaporation. Normal strength concrete (NSC) is highly permeable and easily allows the diffusion of water vapor and this usually causes a reduction in the compression strength. Meanwhile, the pull-out resistance from the fiber can enhance the strength in randomly oriented concrete and also control the cracking and explosive spalling before melting but it is unable to perform these functions after the temperature has passed its melting limit. It is important to note that fiber-reinforced still improve the residual strength of normal concrete [9,15-19] and this is also applicable to a structure subjected to fire.

There is, however, the need to investigate and evaluate the residual strength of fiber concrete after exposure to fire with the focus on its load carrying capacity as a form of mitigation factor in case of significant damage or collapse [9, 20-23]. Mediyanto *et al.* [24] showed the local aluminum fiber made from a piece of wire and used as lightweight concrete was able to improve the compressive strength by 23.70 MPa in comparison with the 20.37 MPa recorded for normal concrete. Moreover, aluminum fiber was also recorded to have shown a higher compressive strength after the lightweight concrete strength was burnt and treated for 56 days. For this study, concrete with aluminum fiber wastes which were produced from the small size of net aluminum sheets usually found in finishing materials and burnt up to 400°C and 800°C to obtain the residual strength. As a limitation, the proportion of aluminum fiber that used in this study is 0.2% where focused on the residual strength of fiber-reinforced concrete exposed to elevated temperature. The scope of this research was to investigate the residual compressive and splitting tensile strength of concrete aluminum fiber at elevated temperatures.

METHODOLOGY

Materials

The concrete specimen was made from Portland cement type I with a standard manufacturing specification according to ASTM C-150 [25], fine aggregate from local natural river sand, coarse aggregate from crushed natural stone, and aluminum fiber. The sieve analysis test showed that the fine aggregate with 3.14 fineness modulus was in zone 2 while the coarse aggregate with a nominal maximum size of 20 mm has a 7.76 fineness modulus [26]. The water absorption and the specific gravity for the sand were 6.61% and 2.56 g/cm^3 while the coarse aggregate had 2.31% and 2.63 g/cm^3, respectively as measured under saturated surface dry condition (SSD). Moreover, the aluminum fiber used in mixing the concrete has 10 mm x 25 mm dimensions and is produced from wire mesh as shown in Fig.1 and the melting point is 660°C based on the assumption that it is pure aluminum alloy [27].

FIGURE 1. Aluminum fiber with 10 mm x 25 mm dimension produced from aluminum net waste.

Mix Proportion and Test Specimens

The specimens were produced using a mix design at a compressive strength (*f'c*) of 25 MPa with 0.5 water ratio, and 3:2 for coarse and fine aggregates. Moreover, the aluminum fiber concrete (ALFC) had aluminum fiber of 0.2% concrete volume while the normal concrete (NC) was without fiber. The flowability of fresh concrete would be evaluated by slump cone test and a decrease in the slump value was observed to have occurred after the aluminum fiber has been added as indicated in Table 1. This reduction was, however, associated with the larger surface area of the fiber which further increased the surface area of the materials lubricated with water [28, 29].

The specimens were later cast into a standard cylindrical container with 150 mm diameter and 300 mm height and treated with water curing up to the age of 28 days. They were placed into the furnace for fire testing after they have dried completely.

TABLE 1. Mix design of NC and ALFC.

Specimen	Cement (kg/m^3)	Water (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Fiber (%)	Slump (mm)
NC	425.13	212.50	663.20	994.80	0	11.67
ALFC	425.13	212.50	663.03	994.55	0.2	8.83

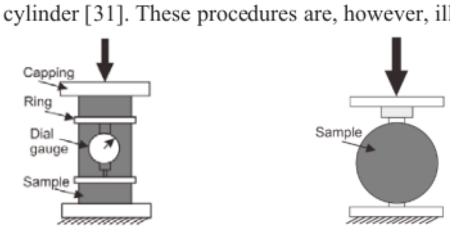
Preparation and Test

The fire test was conducted using a furnace burner according to ASTM E-119 [30] and this involved partial fire exposure of ALFC and NC of 400°C and 800°C. The furnace was set up with one burner and thermocouple near the concrete to measure its temperature during the burning process as shown in Fig. 2. Meanwhile, the concrete was heated up at a constant temperature for 30 minutes and an indicator light was connected to the thermocouple to show when the temperature exceeds this limit to turn the burner off automatically and ensure the temperature drops back to the value designed for the test. In terms of determining the residual strength, the burnt samples were cooled down by remaining in the furnace for 24 hours before the mechanical test was conducted.

(a) (b)

FIGURE 2. The fire test: (a) the concrete specimens inside the furnace, (b) burner setup.

The standard method to evaluate the concrete's properties is by determining the compressive strength and modulus of elasticity. Therefore, the compressive test was obtained using a hydraulic testing machine at a 0.15 MPa/s constant axial compression load and a dial to measure the strain. The tensile strength was obtained by splitting test according to ASTM C496/C496M and this involved placing the specimen in a longitudinal direction after which a vertical load was applied on the entire length cylinder [31]. These procedures are, however, illustrated in the following Fig. 3.



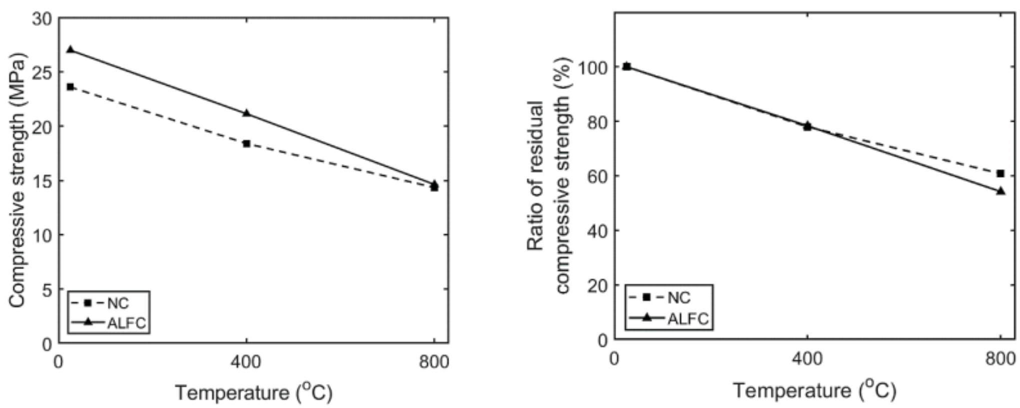
(a) (b)

FIGURE 3. The mechanical test to obtain: (a) compressive strength (b) splitting tensile strength.

RESULTS AND DISCUSSION

Residual Compressive Strength

The high temperature caused by fire exposure influenced ALFC and NC samples to lose their compressive strength as shown in Fig. 4(a). However, the aluminum fibers added to the ALFC effectively resisted the compressive load to 14.37%, 14.90%, and 2.00% at 25°C, 400°C, and 800°C respectively while the ratio of the residual to the compressive strength of ALFC and NC was observed to have decreased to 78.32% and 77.96% respectively at 400°C as illustrated in Fig. 4(b). Moreover, the residual value of specimens was observed to be losing free water at 105°C, obtaining capillary water, and affected due to the changes in the complex chemical and physical effect of Portland cement paste material at elevated temperature [32]. The deterioration of cement microstructure occurred at higher temperature up to 400°C as observed with a reduction in hydration products such as Calcium Silicate Hydrate (CSH) and Calcium Hydroxide (CH) which further caused an insignificant increase in the relation of the capillary pore size to the total pore volume in the concrete [33, 34]. The pores inside the concrete cause a reduced compressive strength value of concrete [32].



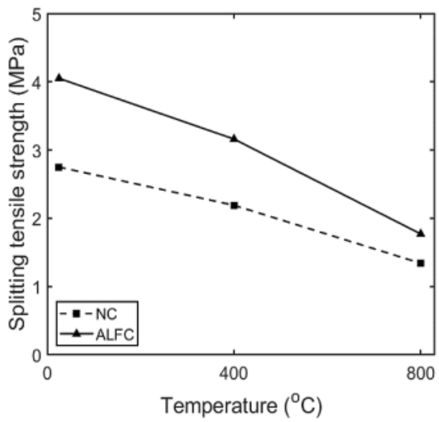
(a) (b)

FIGURE 4. (a) Residual and (b) the ratio of compressive strength of NC and ALFC at 25°C, 400°C, and 800°C to original compressive strength.

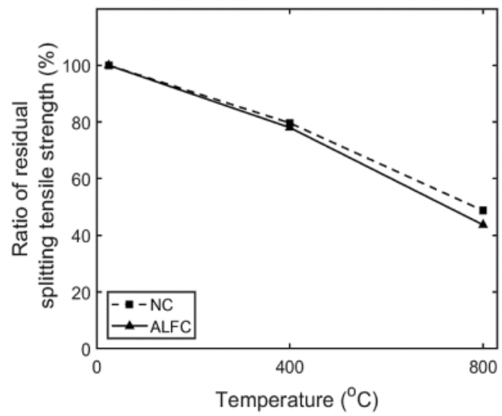
The residual strength of NC was recorded to be 60.78% of the original value at 800°C and, according to several studies, the CSH and CH of Portland cement paste start to rapidly decompose into crystalline particles at approximately 500°C, thereby, causing an increase in the volume of the capillary pore [24, 32-35]. Even though the ALFC slightly carried the load higher than NC, the compressive strength decreased significantly to a residual strength of 54.18% which is lower than the NC value as observed in Fig. 4(b) which shows the huge effect of aluminum fiber on the reduction of concrete's strength. The fiber was observed to have passed its melting point of 660°C as the temperature increased and this led to a micro-scale pore due to the random escape of vapor, thereby, causing a significant reduction in its strength [35, 36]. This was further supported by Li *et al.* [37] which used microscale images to show that the micropores in an ultra-high-performance fiber-reinforced concrete prevent spalling by releasing vapor pressure after the polyethylene (PE) fiber exceeded the melting point. The loss of bond in the concrete matrix due to the melting of PE fibers and microcracking have caused deterioration of mechanical properties significantly.

Residual Split Tensile Strength

The split tensile strength of ALFC and NC decreased when exposed to the temperatures but ALFC had 47.27%, 44.29%, and 32.09% higher than NC at 25°C, 400°C, and 800°C as presented in Fig. 5(a). ALFC was discovered to have residual strength as recorded of 78.62% and 43.70% while NC was 79.63% and 48.72% of the tensile strength at 400°C and 800°C respectively as presented in Fig. 5(b). This, therefore, means the melting of the aluminum fiber at higher temperatures negatively affected the tensile strength.



(a)



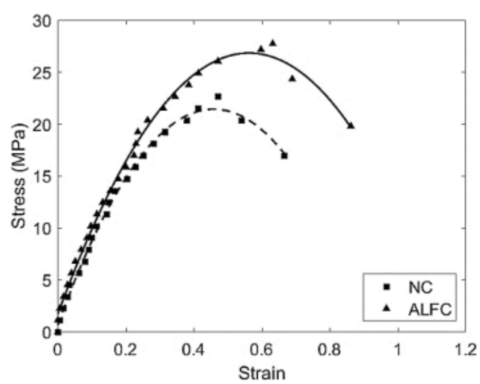
(b)

FIGURE 5. (a) Residual and (b) the ratio of splitting tensile strength of NC and ALFC at 25°C, 400°C, and 800°C to original tensile strength.

The aluminum fiber greatly improved the tensile strength more than the compressive strength as determined by the difference of increments in the strength of NC in Fig. 4(a) and Fig. 5(a). Several studies have shown that concrete has a weak tensile strength but the fiber reinforcement effectively enhanced the pull-out resistance when the concrete was subjected to flexural load [9, 12, 16, 38]. Moreover, the fiber ameliorated the tensile strength as the temperature increased and this was confirmed by Zheng *et al.* [18] which showed steel fiber provided the improvement of the residual tensile strength of concrete due to an increment in the temperature which leads to burning. A similar trend was also observed by Chen *et al.* [36] with the effect of fiber material on the significant decrease in the residual tensile strength after its melting point.

Modulus of Elasticity

The stress-strain curves of all the specimens were obtained using the axial load and strain in compression at 25°C, 400°C, and 800°C for both ALFC and NC are shown in Fig. 6. The addition of 0.2% of fiber aluminum was observed to have led to an increase in the strain at the peak stress and the results were used to determine the modulus of elasticity for the two types of specimens.



(a)

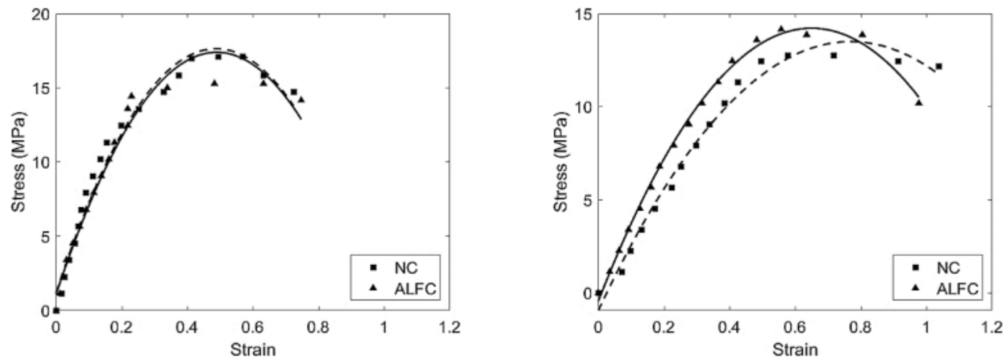


FIGURE 6. Stress-strain curve of NC and ALFC at (a) 25°C, (b) 400°C, and (b) 800°C to the original elastic modulus.

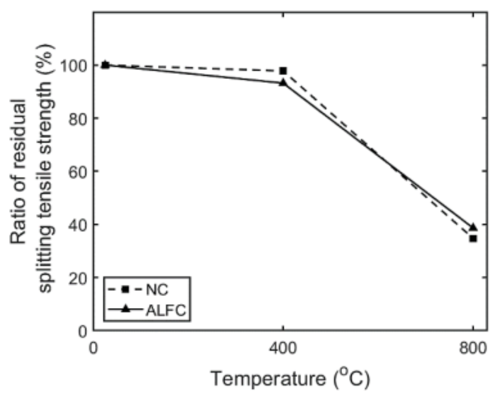


FIGURE 7. The ratio of elasticity modulus of NC and ALFC at 25°C, 400°C, and 800°C to the original elastic modulus

The fibers were discovered to have made the concrete stiffer and the average modulus of elasticity was observed to be significantly reducing as the temperature increased as found with the residual value of 97.80% and 93.21% recorded for NC and ALFC at 400°C. Meanwhile, ALFC was discovered to have performed better with 38.67% at 800°C in comparison with the 34.78% for NC. This is in line with the findings of Verona *et al.* [19] that elevated temperature affected the degradation of modulus of elasticity with the most severe loss recorded at the 400°C to 500°C.

CONCLUSIONS

The residual strength of concretes reinforced with aluminum fibers when exposed to high temperatures was investigated in this research. The aluminum fiber increased the concrete's compressive and tensile strength under the elevated temperature as indicated by the residual strength of the ALFC at 400°C and 800°C. The ALFC's strength was reduced significantly after the melting point of the fiber has been passed but its residual strength was still higher than the value for the NC. Moreover, aluminum fiber was also discovered to be more effective in tensile strength than compressive strength. Therefore, the addition of the aluminum fibers to concrete had effects on the residual strength due to the exposure to high temperatures as observed from the following conclusions:

1. The compressive strength reduced when the temperature was increasing and the ALFC could resist the compressive load more as recorded with 14.37%, 14.90%, and 2.00% in comparison with NC at 25°C, 400°C, and 800°C, respectively. It was also observed to have 78.32% residual strength after reaching 400°C while

NC had 77.96%. Meanwhile, a significant loss of strength was recorded after the fiber passed its melting point and this is indicated by the only 54.18% residual for ALFC and 60.78% for NC.

2. The addition of aluminum fibers also enhanced the tensile strength significantly than the compressive strength, even at elevated temperatures. This was observed in the increment of 47.27%, 44.29%, and 32.09% higher than NC at 25°C, 400°C, and 800°C respectively. Meanwhile, the aluminum fiber influenced quicker loss of strength of ALFC after 400°C with the residual tensile strength recorded to 78.62% and 43.70% while NC was 79.63% and 48.72% at 400°C and 800°C respectively.
3. The stress-strain curve at elevated temperature showed an increase in the strain at the peak stress and the modulus of elasticity of the concrete was also observed to have reduced during the exposure to fire as indicated with the residual value of 93.21% and 97.80% for ALFC and 38.67% and 34.78% for NC at 400°C and 800°C respectively.
4. There is, however, the need to study the combination of different fiber melting points with the ability to resist the melting of the material as well as the effect of the material's geometry and aspect ratio on residual strength at elevated temperatures.

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