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In-situ compressive and tensile performances of high strength engineered cementitious composite at elevated temperatures

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Abstract

The study provides novel insights on the compressive and tensile strength of high strength engineered cementitious composite (HSECC) at elevated temperatures under in-situ testing condition. An optimized mix design was employed and cylinder and dogbone specimens were tested to study the compressive and tensile strength of HSECC at elevated temperature. The tested results under in-situ test condition were compared with the residual state by exposing the specimens to temperature up to 600°C. It was found that specimens under in-situ condition showed a drastic decrease in compressive strength (26.8%–34.5%) at 200°C and the performance was much inferior to that observed for residual state which showed only 12.2% decrease. This trend was consistent for both tensile and compression test results. After this, the in-situ specimens underwent slight increase in the compressive strength with only around 25% decrease at 400°C and 14%–16% decrease at 600°C. However, the residual state specimens underwent continuous decrease in strength. Therefore, this study confirmed that for high strength cementitious composites exposed to elevated temperatures, the residual test results should not be considered as the lower limit and in-situ testing results are essential for accurately predicting the behavior of cementitious composites. Thus, this research underscores the importance of conducting both in-situ and residual state tests in the design of HSECC structural members.

KEYWORDS

elevated temperature, engineered cementitious composite, in-situ test, residual state test

1 | INTRODUCTION

Engineered cementitious composite (ECC) is class of high-performance cementitious, micro-mechanically designed fiber reinforced cementitious composites with high tensile ductility, enhanced durability with crack width less than 100 μm.[1] However, the absence of coarse aggregates in ECC leads to a dense microstructure, making it highly susceptible to fire damage.[2] This vulnerability becomes even more critical for high strength ECC (HSECC) where the matrix is denser due to the resulting hydration products. Consequently, researchers are consistently trying to analyze and

improve the performance of ECC at elevated temperature to broaden its practical implementation.

Simulating the elevated temperature condition experimentally is a challenging task due to the associated complexity of the test setup. Therefore, majority of the current studies focus on testing the specimens in residual state.[3–5] In this approach, specimens are heated to a predetermined temperature and then allowed to cool before testing. This reduces the complexity of the testing setup as a standard muffle furnace can be used to conduct the residual test study. However, it is crucial to consider the in-situ stress state of the ECC specimens during thermal exposure to obtain more realistic results as usually happened in practice. This normally requires preloading the specimen before heating and maintaining it in the test when further loading is applied throughout the temperature exposure. This is known as the *stressed condition* and often relates to the situation when a structural member is subjected to high permanent loads (e.g., heavily load column).[6] Another form of in-situ testing is termed as *unstressed condition* when the specimens are heated without any preloading before the in-situ test is started. It represents the situation when a lightly loaded structural element is subjected to fire. Both unstressed and stressed testing conditions demand more complex experimental setup than residual testing condition and hence, the latter has been more often employed in the reported studies.

Some studies have investigated the effect of different testing conditions (i.e., in-situ vs. residual) with most focusing on and limited to concrete.[6–15] One of the initial studies in this field dates back to 1956, where Malhotra[7] compared the effect of all three-test procedures (residual, stressed, and unstressed) on the strength of normal strength concrete (NSC). They found that the unstressed and residual tests, with unstressed being less severe, may lead to greater decrease in the post-exposure strength as compared to stressed specimens. This was due to the restraint caused by the compressive stress in the free development of cracks when applied simultaneously with the heat load. Phan and Carino[8] later analyzed this effect on the behavior of high strength concrete (HSC). The relative strength loss was found to differ at different temperatures for all three testing conditions. At the lower temperature range of 100–200°C, unstressed condition showed highest strength loss (28%–31%), whereas the residual test condition exhibited the lowest loss (19.0%–19.7%). However, at higher temperature of around 450°C, the strength loss was highest for the residual testing condition. Fu et al.[9] extended this investigation and verified that the compressive strength of stressed test condition was generally higher than stressed tests. Hager and Pimienta[10] further corroborated these observations and noted that in-situ test showed lower strength until 120°C, after which the strength was higher in comparison to the residual state specimens. Persson[11] also examined the effect of in-situ and residual testing condition on the strength of self-compacting concrete. Contrary to the other observations, the residual strength was found to be lower up to 800°C. However, there was very little difference in the strength at both testing conditions until 300°C.

A limited number of researchers have also studied the effect of testing conditions on fiber reinforced concrete. Bamonte and Gambarova[12] compared the effect of unstressed and residual state test condition on the performance of polypropylene (PP) fiber reinforced concrete. It was observed that the unstressed in-situ test led to higher loss in strength in comparison to the residual tests between 100 and 250°C. Unstressed test specimens experienced a strength loss of around 30%, while the residual test specimens only showed a loss of around 2%–3%. At higher temperatures of 300–450°C, there was no statistically significant difference in the strength between both testing condition. Tao et al.[14] also performed similar study on PP fiber reinforced concrete and analyzed the effect of unstressed and stressed testing conditions on the compressive strength. Both testing condition showed similar loss in strength of around 10% between 20 and 200°C. After 400°C, the reduction in compressive strength of unstressed test specimens was higher than stressed test condition. Kim et al.[15] analyzed the effect of test condition at preload level of 0%, 20%, 40% on the compressive strength of PP fiber reinforced concrete. They also observed that the concrete with preload results in better energy absorption capacity. However, the difference between the preload and no-preload case decreases with increase in ambient compressive strength of concrete.

Based on the previous findings, it is evident that the testing condition may lead to a significant change in the resultant compressive strength. Moreover, the effect of in-situ testing could be critical in determining the safe strength reduction factor especially at lower temperature range. Hence, it becomes essential to analyze the impact of testing condition on the mechanical properties of HSECC, particularly due to its vulnerability to fire damage. Currently, the studies focusing on the assessment of in-situ mechanical performance of ECC are scarce, with most literature focusing on the residual state parameters. Moreover, while previous research on elevated temperature studies has predominantly centred on assessing compressive strength, which is the most critical mechanical property for cementitious composites, tensile strength has also been highlighted as crucial parameters for both HSC and fiber reinforced concrete.[16–18] In fact, tensile performance at elevated temperature holds greater significance in case of ECC due to its distinctive strain hardening characteristics. Therefore, this study aims to compare the effect of the in-situ (stressed and unstressed) and residual

test states on the compressive strength of hybrid polyethylene and steel fiber reinforced HSECC at elevated temperatures. Additionally, the study also compares the tensile performance of HSECC under in-situ and residual test status. An optimized mix developed in authors' previous study with a quaternary blend of slag, fly ash, and dolomite has been adopted to analyze the effect of different testing procedures.[16] Standard cylinder and dogbone specimens were tested under in-situ state in order to obtain important insights on the influence and severity of testing condition.

2 | EXPERIMENTAL PROGRAMS

2.1 | Mix proportion

Table 1 outlines the mix composition utilized in the present research. The authors recently developed this particular mix containing cement, ground granulated blast furnace slag (GGBFS), fly ash (FA), and dolomite through multi-response optimization, where it exhibited impressive compressive and tensile performance under ambient temperature conditions.[19] The oxide composition of these matrix ingredients is further shown in Table 2. This mix also demonstrated superior spalling resistance in comparison to the conventional silica fume mix.[20] Due to these promising attributes, the same mix design was adopted in the present study.

2.2 | Specimen preparation and test methods

Mixing of the constituents was done in a 100-L pan type mixer as per the procedures stated in Rawat et al.[19] Firstly, all dry ingredients were mixed for approximately 1 min. The appropriate quantity of HRWR was separately diluted and mixed with the measured water. Subsequently, around 10% of this solution was slowly introduced into the mixture to minimize the powder plume and mixing continued for the next 2–3 min. The remaining solution were then gradually added during mixing until a uniform and homogenous mortar was achieved with no visible lumps. Following this, the required amounts of steel and PE fibers were added in stages and mixing continued for another 8–10 min to ensure a homogeneous dispersion of fibers. The 75 mm diameter × 150 mm height cylinders were cast for the compression tests. Dog-bone specimens measuring 368 × 80 × 20 mm with a reduced section of 100 × 35 × 20 mm in the middle were used to measure the tensile behavior. All samples were cured at 23 ± 1°C and 95 ± 5% relative humidity for 28 days and at 20°C and 55% relative humidity for another 28 days. Three specimens were tested for each set to ensure a statistically significant average.

2.2.1 | Residual state testing at elevated temperature

For the residual state tests, cylinder specimens were heated to 200, 400, and 600°C and dogbone specimens were heated to 200 and 300°C in a standard muffle furnace. The heating was done at a constant rate of 1°C/min and dwell duration of 2 h as shown in Figure 1. After the dwell period, the specimens were allowed to cool naturally and then tested for compression or tension strength by using standard testing procedures.[19]

2.2.2 | In-situ compressive testing at elevated temperature

Vertical split tube furnace with a 1000 kN capacity hydraulic jack was employed for the in-situ compressive

TABLE 1 Mix proportions used in present study.

Binder								
Cement	GGBFS	FA	Dolomite	Fine sand	Water	HRWR	PE (% vol.)	Steel (% vol.)
1	0.94	0.19	0.38	0.91	0.50	0.05	1.50%	0.75%

Note: HRWR, high range water reducer; PE, polyethylene fiber (length 12 mm, aspect ratio 500), and steel fibers (length 13 mm, aspect ratio 65).

TABLE 2 X-ray fluorescence (XRF) analysis of the binder material.

Element	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Loss on ignition
Cement	63.74	18.51	5.11	2.92	0.92	0.13	0.36	2.64	4.97
GGBFS	41.25	34.38	13.31	0.71	4.75	0.35	0.28	2.85	<0.01
FA	1.46	67.62	19.94	3.70	0.53	0.61	2.23	0.05	2.02
Dolomite	30.50	1.82	<0.01	0.05	21.70	0.19	<0.01	<0.01	45.62

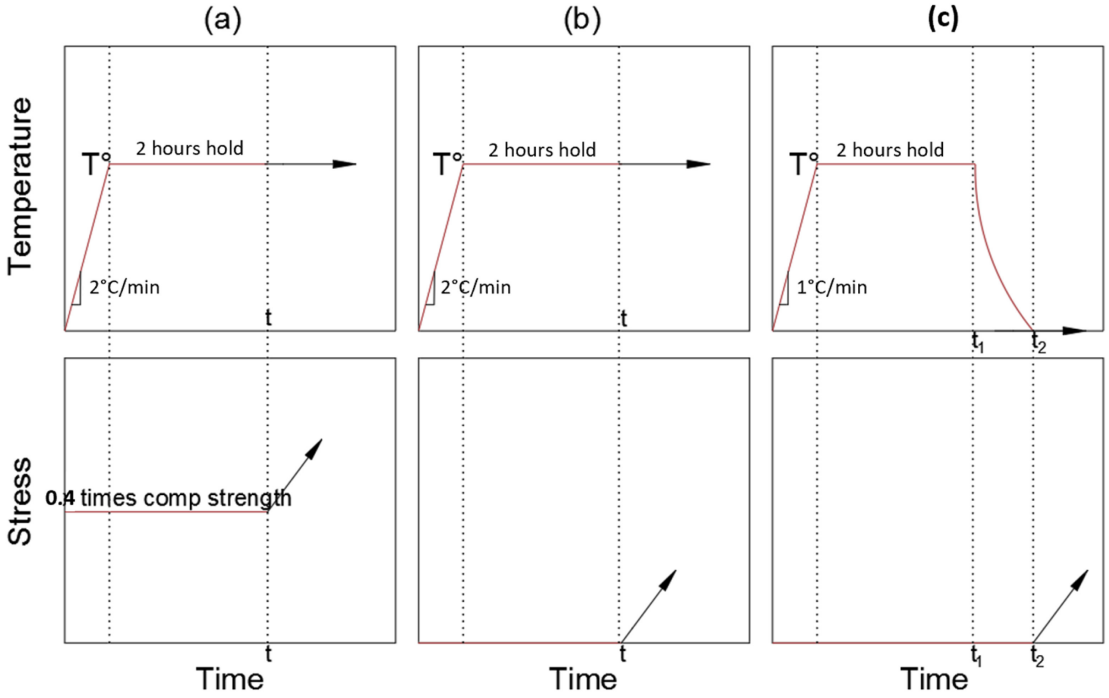

FIGURE 1 Types of elevated temperature tests: (a) stressed; (b) unstressed; (c) residual.

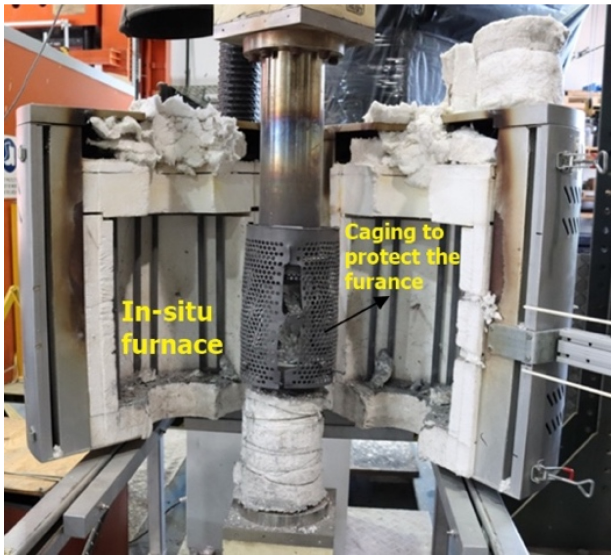

FIGURE 2 Set up for in-situ compression tests.

strength tests at elevated temperature. A steel casing was also installed after the cylinder sample was steadily put on the lower holder to avoid any damage to the furnace (Figure 2). Two types of tests were considered in this case.

a. In-situ stressed test

In this type of testing, a preload equal to 40% of the room temperature compressive strength was applied to the specimens prior to heating and thereafter, the specimens were exposed to 200–600°C at a heating rate of 2°C/min.

b. In-situ unstressed test

In this type of testing, no preload was applied, and the specimens were directly exposed to 200–600°C at a heating rate of 2°C/min (Figure 1). After attaining the set temperature, the temperature was sustained for another 2 h and thereafter, the specimens were loaded under compression at a loading rate of 0.027 mm/s until failure.

2.2.3 | In-situ tensile testing at elevated temperature

The in-situ uniaxial tensile tests at elevated temperature were performed in the 100 kN capacity Shimadzu AG-X machine at a loading rate of 0.1 mm/min. The testing assembly contained jigs to fit the specimen inside the oven, a laser distance meter, a thermocouple, and a motor with two pipes connected to the bottom of the load cell to avoid overheating damage. A laser distance meter was used to measure the strain during in-situ tests as shown in Figure 3. All the specimens were preloaded to 100 N before the start of the test to avoid any possible misalignment due to high temperature. Thereafter, the specimens were subjected to the thermal exposure of 100–300°C at a rate of 2°C/min with a 2-h hold duration

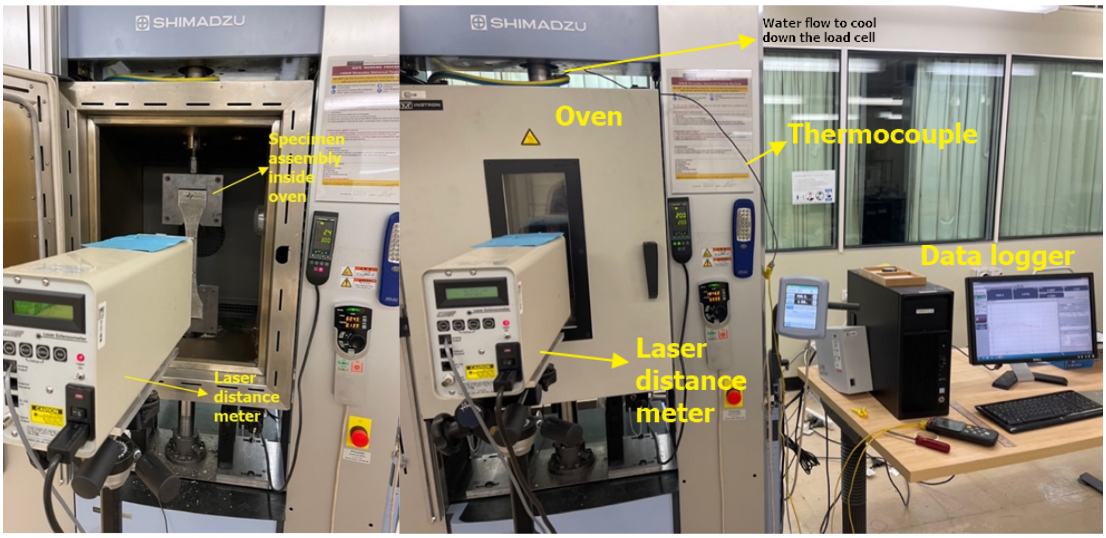

FIGURE 3 Set up for in-situ tensile tests.

(Figure 1b). Heated specimens were then loaded until failure in an unstressed state. The load and corresponding strain were recorded using a data logger as shown in Figure 3.

3 | RESULTS AND DISCUSSION

3.1 | Residual and in-situ compressive behaviors

Table 3 shows the observed compressive strength of cylinder specimens at ambient and elevated temperatures. It can be seen that the compressive strength decreased with increase in temperature, with in-situ specimens experiencing a more pronounced reduction than residual state specimens. A clearer understanding could further be obtained through Figure 4 which depicts the relative variation of in-situ and residual compressive at different temperature range with respect to the ambient temperature compressive strength. It should be noted that the normalized compressive strength (Figure 4) is defined as the ratio of the compressive strength at a specific temperature to the ambient temperature compressive strength of the specimen of same batch. Notably, the in-situ strength decreased significantly at the initial exposure to 200°C. A decrease of around 26.8% was observed for the unstressed test, whereas the strength reduced by approximately 36.5% for the stressed test. This decrease was substantially higher than the residual test reduction of only 12.2%. The difference in the in-situ and residual tests may have been due to the vapor pressure inside the HSECC. The residual state specimens were cooled before the compression tests allowing sufficient time for the vapor pressure to release.

TABLE 3 Compressive strength of ECC mix under different testing conditions (in MPa).

	20°C	200°C	400°C	600°C
Residual	138.1	121.26	106.87	95.68
In-situ				
Unstressed	124.65	91.22	103.15	117.57
Stressed	124.65	81.63	92.32	103.69

Note: The ambient temperature compressive strength of the 600°C batch specimen was 126.85 MPa.

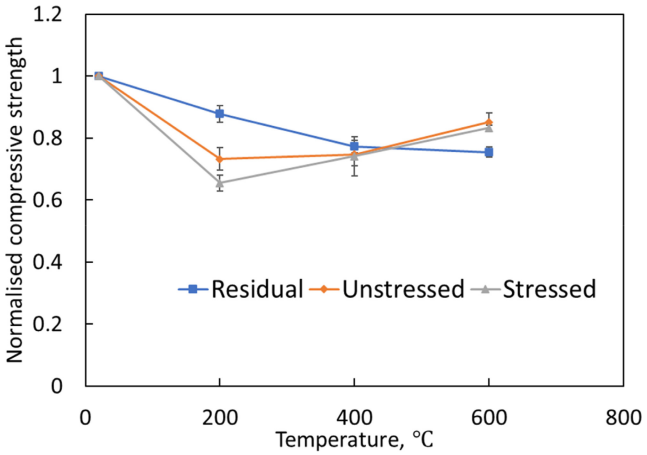

FIGURE 4 Effect of type of testing on HSECC specimens at elevated temperatures.

However, when the specimens were tested under in-situ condition, the interaction between the vapor pressure and the simultaneously applied compressive load led to a large decrease in compressive strength.

On increasing the temperature to 400°C, the difference between the residual and in-situ tests subsided. The specimens under unstressed and stressed testing conditions only suffered a decrease of around 25.3% and 25.9% respectively at this temperature. Moreover, the strength of both stressed and unstressed state specimen was higher than that observed at 200°C. Tao et al.[14] also observed this trend and suggested the increasing trend after 200°C could be as a result of the increase in the surface forces between gel particles due to removal of absorbed moisture. At 600°C, the strength further increased for both stressed and unstressed state specimens and only around 14%–16% decrease in the compressive strength was observed. This trend was opposite to trend observed at 200°C as the residual state specimens suffered higher decrease of approximately 24.6%. At higher temperature, the influence of vapor pressure might have become insignificant mainly because the evaporation rate stabilized, and the PE fibers were also completely vaporized leaving clear channels for vapor passage. Instead, the decomposition of the matrix becomes more pronounced, potentially amplified by the presence of microcracks and deterioration that occurs during the slow cooling phase and hence, the residual state specimens might have suffered higher decrease. The overall effect can be summarized as below.

- At 200°C, the residual test condition resulted in smallest strength loss and the stressed condition showed the highest loss. This is likely attributed to the combined impact of vapor pressure and compressive load, leading to a more substantial reduction in in-situ strength. During the initial temperature increase, the higher evaporation rate increases the likelihood of greater vapor pressure. Additionally, PE fibers remain in a molten state, potentially hindering pressure release and causing increased stress within the specimen. On the other hand, the residual state specimens had sufficient time for the vapor pressure to release, which may have prevented the severe decrease.
- At 400°C, statistically there was no difference in the strength loss measured by the three test conditions. At this stage, the impact of vapor pressure diminishes as the fibers move toward vaporization state, resulting in a less severe effect on in-situ testing compared to 200°C.
- At 600°C, the highest loss was measured for the residual test condition and there was no statistically significant difference in the stressed and unstressed test condition results. During this stage, the decomposition of the matrix becomes more prominent than vapor pressure. Therefore, the residual state specimens suffer more deterioration as the matrix decomposition continues for an extended period (during the cooling phase).

These observations can further be confirmed through the visual analysis of specimens failed under compression as shown in Figure 5. At 200°C, the failure in the in-situ test (both stressed and unstressed) specimens was explosive with a loud bang sound, whereas the residual test specimens showed a similar failure pattern as the control specimens which was tested at room temperature with multiple interacting cracks. The crack width at the failure for in-situ specimens tested at 400°C was more severe due to the developed vapor pressure. However, the difference between the residual state and in-situ test specimens was not as noticeable as that observed at 200°C. At 600°C, both types of testing led to similar kind of failure showing multiple interacting cracks with increased crack width.

3.2 | Comparison with existing studies and international standards

The significance of the in-situ testing condition could further be highlighted through a comparison with the observations from the previous research on high strength PP fiber reinforced cementitious composite (PP-FRCC)[21] and strength reduction factor reported in the international standards as shown in Figure 6. The values from different standards namely ACI 216.1,[22] EN 1992-1-2,[23] and the Concrete Association of Finland's RakMK B4[24] have been compiled and compared with the obtained results. It can be observed that though the performance of tested HSECC was better than PP-FRCC specimens,[21] the in-situ strength for both type falls at the lower end of the strength reported in the standards showing the severity of the testing condition. The strength was considerably lower for both unstressed and stressed condition and particularly especially at 200°C. Given that the stressed condition more accurately represents the service state of a structure, the comparatively lower value for HSECC underscores the necessity of factoring in the in-situ testing for studies conducted at elevated temperatures.

3.2.1 | Residual and in-situ tensile behavior

The in-situ tensile stress–strain responses of the HSECC dog bone specimens are shown in Figure 7. Generally, all stress–strain responses followed three stages: (a) initial elastic stage whereby the tensile stress continuously increased before experiencing the first crack, (b) strain hardening stage whereby the specimens consistently underwent multiple fine cracks showing minor rise and drop of the tensile stress with increasing strain, and (c) strain softening stage due to the localization of failure at one of the

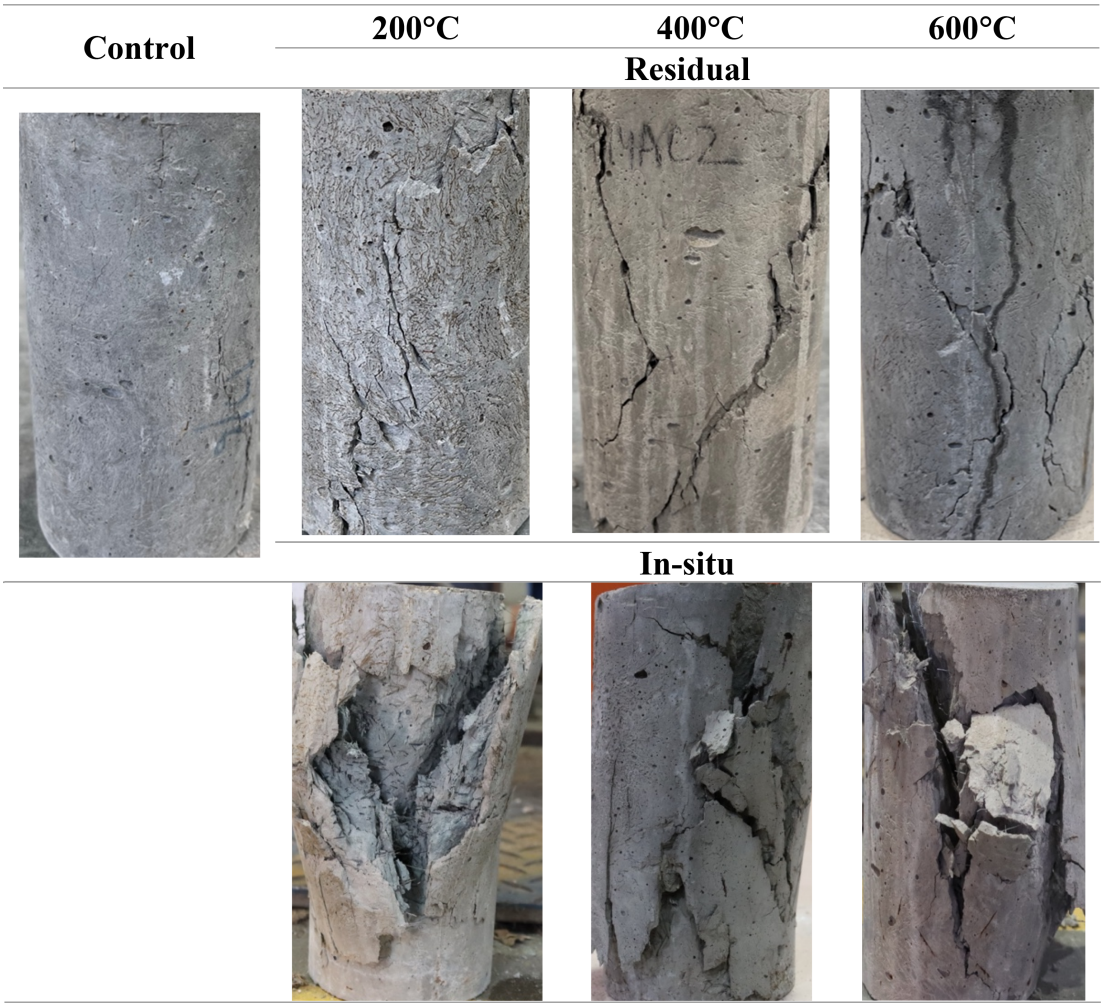

FIGURE 5 Comparison of the failure pattern in HSECC specimens tested under in-situ and residual conditions.

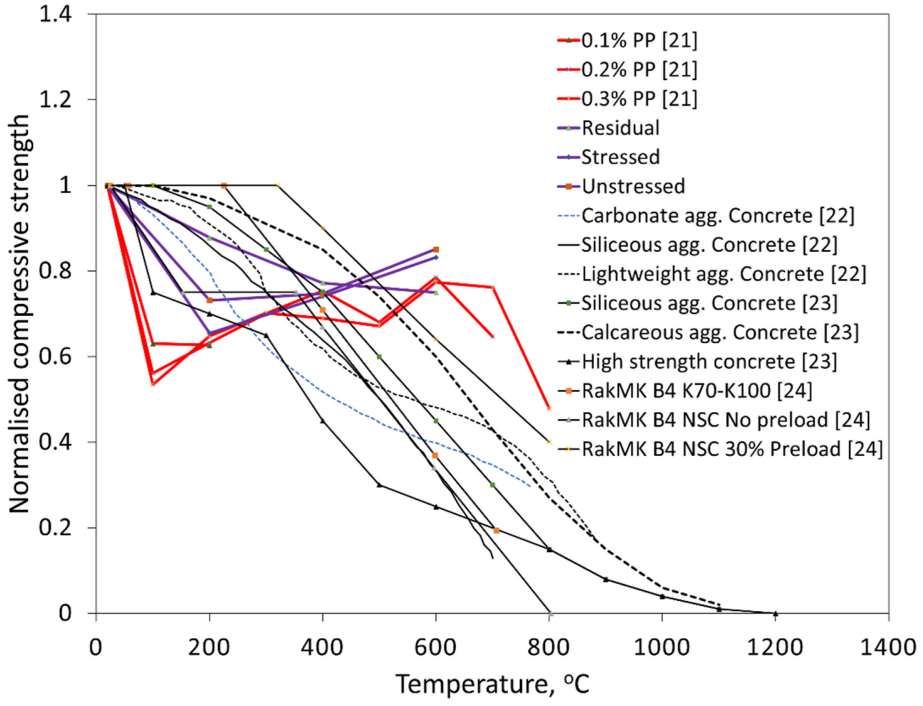

FIGURE 6 Comparison of the normalized compressive strength with that of standard strength reduction factors at elevated temperatures.

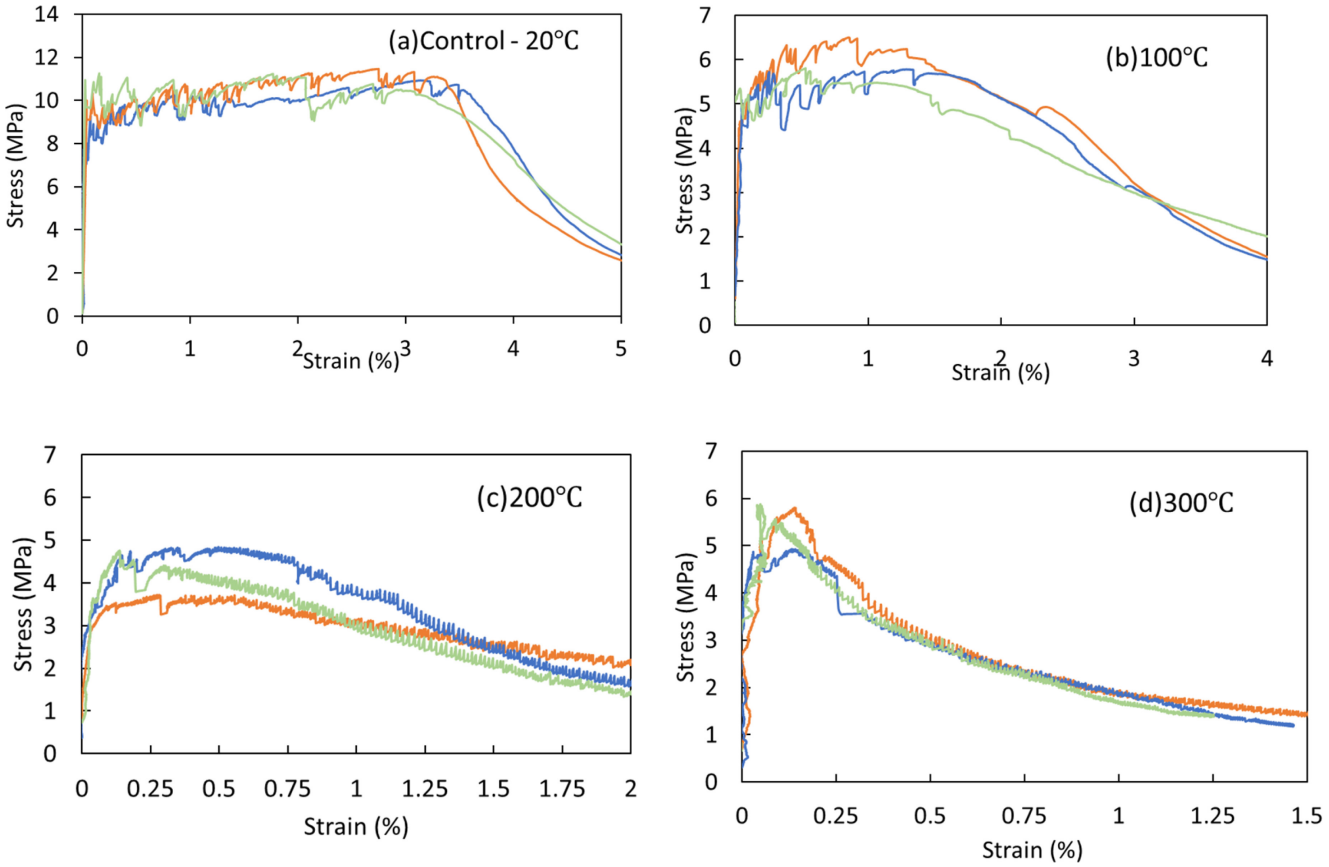

FIGURE 7 In-situ tensile stress–strain behavior at different temperatures.

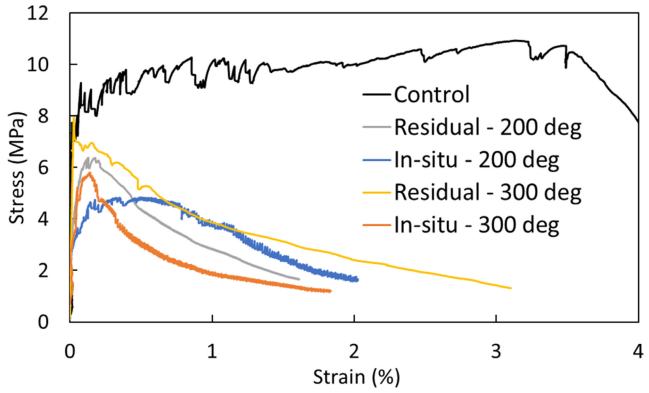

FIGURE 8 Tensile stress–strain behavior at residual and in-situ state.

cracks which continued until the test is stopped. It can be observed that with increase in the temperature, both tensile strength and strain hardening region reduces drastically. Contrary to observations of the residual tensile tests as shown in Figure 8, strain hardening region was partially evident till 200°C which thereafter reduced to strain softening behavior at 300°C.

The results of the in-situ and residual tensile tests can be further compared in Figure 9. It can be seen that the tensile strength loss is much higher in the in-situ test specimens. The in-situ tensile strength reduced to 42.2% of the control tensile strength at 200°C, whereas retention for residual test was up to 52.4%. When testing temperature was increased to 300°C, there was a slight improvement in the tensile strength for both testing conditions (Figure 9a). In-situ tensile strength increased by 1.27 times whereas this increase was 1.61 times for the residual test specimens. The ultimate tensile strain also showed different variation (Figure 9b). The ultimate strain reduced from 3.42% to 0.91% and 0.24% at 200°C for the in-situ and residual condition, respectively. The difference in both testing condition subsided at 300°C where the ultimate strain of 0.25%–0.4% was observed.

Overall, the effect of the in-situ testing type on tensile strength is similar to that observed in compressive strength. Evaporation of water plays critical role during the initial temperature range of 100–300°C in the generation of pore pressure. The complex interaction between external tensile stress and inbuilt pore pressure may have led to significant decrease in the tensile strength. On the other hand, the ultimate tensile strain is dependent on the softening point and melting point of fibers. During the in-situ testing, the fibers may have been in molten

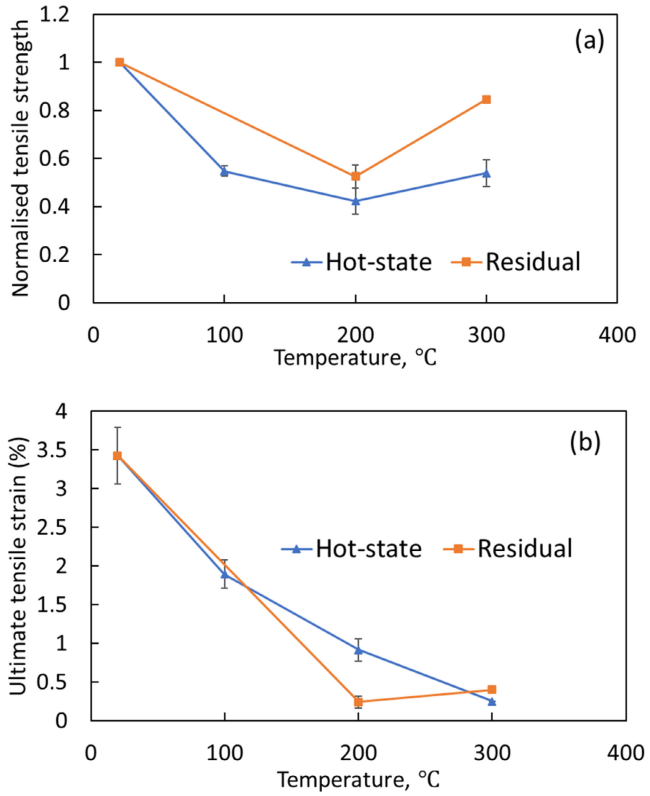

FIGURE 9 Comparison of the in-situ and residual (a) tensile strength and (b) ultimate strain at elevated temperatures.

state leading to a partial demonstration of the hardening and softening behavior. This effect was not as prominent in the residual state specimens, where the cooling process may have diminished such behavior.

4 | CONCLUSIONS

This paper focused on experimentally investigating the in-situ compressive strength and tensile strength performances of HSECC at elevated temperatures and comparing the results in different testing conditions. The findings indicated a substantial decline (26.8%–34.5%) in the strength of in-situ test specimens at 200°C compared to the residual test specimens, which experienced only 12.2% decrease. However, as the temperature increased, this trend reversed, and the performance of in-situ specimens were found better than at 200°C with only around 25% decrease. At 600°C, the in-situ strength surpassed the residual strength showing only 17% decrease, whereas the residual strength decreased by 25%. The in-situ tensile strength displayed a similar trend, showing an increasing trend after 200°C and a higher loss in strength than the residual state from 100 to 300°C. Additionally, the strain hardening behavior in HSECC was partially evident until 200°C, but it transitioned to a strain softening behavior at 300°C.

The results under different testing conditions clearly highlight that a complex interaction may occur between the external stresses and the internal pore pressure during in-situ testing especially during initial rise in temperature (<400°C) when the rate of evaporation is very high. However, this phenomenon is not encountered in the residual state as the specimens have sufficient time to cool adequately. As a result, the test results may significantly differ depending on the testing condition. Therefore, future studies must consider this aspect when designing HSECC materials for fire resistance.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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