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Structural Engineering and Mechanics, *Vol. 94, No. 6 (2025) 479-494*
https://doi.org/10.12989/sem.2025.94.6.479

Performance enhancement and post-fire behavior of concrete incorporating waste fire clay as sustainable solution

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(*Received December 5, 2024, Revised May 11, 2025, Accepted May 12, 2025*)

Abstract. Waste fire clay (WFC) was selected for use in this research study as a substitute for fine aggregate (FA) and cement in certain amounts. For this purpose, the amounts of FA and cement in the mixture were replaced with WFC (10%, 20%, 30%, 40% and 50%), while the effect of temperature on strength was also investigated. Regarding the temperature impact, variations of 24°C, 300°C, 600°C, and 900°C were taken into consideration. As a consequence of these alterations, the concrete mixture's flexural strength (FS), splitting tensile strength (STS), and compression strength (CS) were measured and assessed. Consequently, the investigations conducted on the test samples revealed that the CSs rose by up to 30% due to the substitution of WFC in the combination with FA. The rise rates are 11.11%, 16.31%, 19.03%, and 5.79%, respectively. The final mixture ratio of 50% exhibited a consistent reduction of 13.34% relative to the reference sample (34.57 MPa). When cement was added to the mixture in place of WFC, the CSs steadily dropped in comparison to the reference sample (34.57 MPa). The relative decrease rates are 6.74%, 13.65%, 30.14%, 42.26%, and 62.08%. The strength of the combination was shown to decrease with rising temperature values for both FA change and cement change. It was determined that the ultimate strength of concrete was achieved by a 30% substitution of WFC with FA, and a 20% substitution of WFC with cement. Comparative FE-SEM analyses were conducted on concrete that was substituted with FA and cement. FE-SEM analysis showed that increasing chamotte content resulted in denser microstructures with gel-like and acicular crystalline phases formed. The EDX results confirmed the presence of Si, Al and Ca as the main elements, indicating the co-existence of binding phases of the C-S-H and C-A-S-H type.

Keywords: cement; elevated temperature; fine aggregate; fire clay; SEM; waste

1. Introduction

The waste recycling procedure is crucial for the mitigation and elimination of detrimental environmental impacts. The utilization of recycled waste as building materials is recommended by recent research and technological advancements, considering both environmental factors and construction methods. This context has resulted in a substantial increase in the demand for fired clay bricks as materials for construction in recent years. Numerous studies have been conducted in the literature to investigate the replacement of fire clay with aggregate and cement in varying proportions. Nevertheless, there are precious few studies that examine the tensile properties of materials at varying temperatures. One of these investigations was conducted by Chindaprasirt *et al.* (2021). The present paper examines the compressive strength and physical characteristics of fire clay bricks that are composed of a concrete mixture that includes fly ash, glass cullet, and clay bricks, all of which are combined at varying temperatures. The temperature effect was investigated by producing clay bricks at 950, 1050, and 1100°C by incorporating fly ash and glass cullet at rates of 0%, 2%, 4%, 6%, and 8% of the clay weight. The findings showed that when the firing temperature and fly ash-glass cullet concentration rose owing to densification, the bricks burned at 950-1100℃ gained strength. Lawanwadeekul *et al.* (2023) performed another investigation. The purpose of this study is to examine the variations in porosity and strength of clay bricks as a result of igniting the clay mixtures at 900, 1000, and 1100°C and the influence of maize cob and waste glass on temperature. Within this investigation, fire clay bricks' thermal, mechanical, and physical characteristics were thoroughly examined. It was determined that the compressive strength values of fire clay brick samples significantly increased as a consequence of the increased waste glass percentage in the combination and the increase in oven temperature. Additionally, the microstructures of the specimens that were fired at 1100°C were identified as denser than those that were fired at 900°C. Abdullah and Mohammed (2023) examined how the behavior of concrete exposed to fire at temperatures of 300, 400, 500, and 600℃ was affected by substituting different percentages (0, 10, 20, and 30%) of light expanded clay aggregate for coarse aggregate. After being subjected to temperatures that are higher than 300℃, it has been shown

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ISSN: 1225-4568 (Print), 1598-6217 (Online)

that the compressive strength of concrete experiences a substantial drop. One explanation for this phenomenon is that concrete becomes dehydrated as a result of the water loss. Furthermore, the thermal expansion of concrete and its constituents results in the formation of internal stresses and fractures that compromise concrete's structural integrity. The final explanation is the chemical decomposition of certain concrete components, including calcium hydroxide and calcium silicate hydrate, which results in a reduction in the cementitious properties of the concrete. Another investigation was performed by Tsega *et al.* (2017). In this study, the impact of varying temperatures on the mechanical characteristics of bricks was examined via a variety of experiments. For this purpose, mechanical tests were carried out by exposing the test samples to the temperature effect in the oven at 700, 970 and 1200℃. Based on the information gleaned from the test results, it was noted that the CS increased quickly at 700°C. The primary cause was identified as the vitrification phenomenon. Karaman *et al.* (2006) examined how temperature and firing duration affected the properties of clay bricks, including density, weight loss, flexural strength, water absorption, compressive strength, and firing shrinkage. According to this research, 700ºC was the lowest temperature required to fire bricks, and firing procedures were conducted in an electric oven at 700-1100°C in increments of 100°C. It was found at the conclusion of the investigation that is on fire the brick at higher temperatures might greatly increase its compressive strength. Furthermore, when the firing temperature escalated, the compressive strength augmented by 31.1% at 700-800°C and by 253.3% at 700-1100°C. The significant increase in strength at temperatures of 1000°C and higher was ascribed to the enhanced vitrification of the clay components. Additionally, at firing temperatures higher than 900ºC, significant improvements in bending strength were noticed. Bhatnagar and Goel (2002) performed another investigation. To assess the thermal alteration of clay products used in brick manufacturing, experiments were conducted on samples subjected to various firing temperatures (700, 800, 900, 1000, and 1100°C). It was found at the conclusion of the investigation that when the firing temperature was raised from 700 to 1100°C, the specimens' strength rose but their water absorption decreased. Another significant finding from this investigation is that specimens fired between 700 and 800°C showed a rise in compressive strength of around 12-17% of the maximum strength at 1100°C. It was noted that the strength gain in the samples increased to 30% and 60% of the ultimate value at 1100℃ when the temperature was raised to 900°C and 1000°C, respectively. The cause was identified as the heightened vitrification inside the body. Cultrone *et al.* (2004) performed research to examine the correlations among raw clay composition, firing temperature, porosity, and particle size distribution of solid bricks. In this investigation, test materials were subjected to baking in an electric furnace at temperatures of 700°C, 800°C, 900℃, 1000℃, and 1100°C. The research concluded that lime-free clay burnt at temperatures over 1000°C exhibited the optimal hydric characteristics, serving as indicators of technical excellence and durability. Phonphuak (2013) performed an examination of the thermal, mechanical, and physical characteristics of fired clay bricks. For the purpose of examining the thermal performance, mechanical, and microstructure properties, all samples were fired at 950°C. Consequently, it was noted that the density of fired clay bricks reduced by as much as 10%, contingent upon the percentage. Furthermore, it was determined that an increase in firing temperature correlates with enhanced compressive strength of the burnt bricks. Measurements of thermal conductivity were conducted on fired specimens of each parts of clay by Gualtieri *et al.* (2010). The prepared samples were subjected to temperature effects by heating them in an electric furnace from 25°C to 850°C for 8 hours, followed by a long isotherm at 850°C for 30 minutes, and then chilling them to 25°C for 1.5 hours. At the conclusion of the investigation, it was noted that during the fire process, a rise in sintering speed resulted in a reduction of thermal insulation concomitant with a drop in particle size. In addition to these investigations in the literature, Baspinar *et al.* (2010) conducted a research to examine the effects of temperature on fired clay and the reactions of varying silica fume additions on the characteristics of burned clay bricks. For this reason, test samples were created using the uniaxial pressing technique, and then they were subjected to the temperature effect at temperatures of 800, 900, 1000, and 1100°C. The influence of mixture proportions on strength was examined by incorporating several quantities of silica fume (0%, 2.5%, 5%, and 10%) into the original brick clay throughout the experiment. Experiments conducted at elevated temperatures revealed that test samples exhibited denser microstructures in the fired clay body at higher firing temperatures. The researchers determined that the elevation in firing temperature markedly decreased the overall pore capacity in the test sample due to the augmentation of the glassy phase in the fired brick bodies. Bidoung *et al.* (2016) investigated the mechanical and thermal behavior of traditional clay bricks at 3 different temperatures, 200, 400, and 600°C. Six samples were also subjected to compression testing in addition to that. Analyzing the brick surfaces under an optical microscope showed that, up to 600°C, their porous structure remained rather constant. When the results are examined in terms of mechanical strength, a slight decrease occurs up to 400°C, while there is an increase in strength between 400 and 600°C. The reason for this is explained by the observation of an increase in the porosity of the specimen compared to its value at room temperature. Bidoung *et al.* (2023) also performed another investigation to observe the strength of fired clay. During the experiments, the temperatures were determined as 29°C. 95°C. 200°C. 550°C. 700°C and 950°C and the tests were carried out under these temperatures. While an increase in elastic modulus was observed up to 95°C, a sudden decrease was observed after this temperature up to 950°C.

In the literature, there are a great number of research (Keerthinarayana and Srinivasan 2010, Aliabdo *et al.* 2014, Dhanalakshmi 2015, Ge *et al.* 2015, Nisha Devi 2016, Rani and Jenifer 2016, Vaitheki *et al.* 2019, Kesegić *et al.* 2008, Wongsa *et al.* 2018, Šebestová *et al.* 2019, Joyklad *et al.*

Table 1 Mix proportions for fine aggregate replacement (kg)

Mix	Cement	Water	Fine Aggregate	Coarse Aggregate	Fire Clay
0%	600	300	600	720	0
10%	600	300	540	720	60
20%	600	300	480	720	120
30%	600	300	420	720	180
40%	600	300	360	720	240
50%	600	300	300	720	300

Table 2 Mix proportions for cement replacement (kg)

Mix	Cement	Water	Fine Aggregate	Coarse Aggregate	Fire Clay
0%	600	300	600	720	0
10%	540	300	600	720	60
20%	480	300	600	720	120
30%	420	300	600	720	180
40%	360	300	600	720	240
50%	300	300	600	720	300

2018, Ramkumar and Manikandan 2022) on fire clay, as can be observed from the studies that were shown before. There are also limited studies (Rodsin 2021, Li *et al.* 2023, 2024, Özkılıç *et al.* 2023) which use WFC in structural members and also there are studies which generally carried out by adding fire clay to the mixture with another additive (Isah 2014, Gencel 2015, Kadir and Mohajerani 2015, Sutcu *et al.* 2015, Phonphuak *et al.* 2016, Anjum *et al.* 2019, Pitak *et al.* 2022).On the other hand, the number of research that have been carried out on the examination of mechanical characteristics, particularly with regard to the influence of temperature, is rather limited. In this respect, this study will contribute to the literature.

2. Material methods

Waste fire clay was added to the concrete mixture with percentages of 0%, 10%, 20%, 30% 40% and 50%. Waste fire clay was altered with fine aggregate and cement with weight proportions. For reference sample, water/cement ratio was selected as 0.5 and cement to total aggregate ratios was utilized as 0.46. The mixture proportions for 1 m^3 is shown in Table. Cement of CEM 32.5 was utilized. The size of fine aggregate was 0-4 mm while the size of coarse aggregate was 5-12 mm. The samples were exposed to elevated temperature before testing. Three different elevated temperatures of 300°C, 600°C and 900°C. The utilized oven depicted in Fig. 1 was big enough to expose to the elevated temperature equally on the samples. After exposing elevated temperatures, the samples were tested under compression, tensile splitting and flexural tests as shown in Fig. 2.

3. Analysis of experimental tests and discussion

Cement and fine aggregate were combined with waste fire clay in weight percentages of 0%, 10%, 20%, 30%, 40%, and 50% for this investigation. Furthermore, the samples were subjected to three distinct high temperatures of 300°C, 600°C, and 900°C prior to the testing. Following exposure to extreme temperatures, the samples conducted flexural, tensile splitting, and compression testing. The following sections provide comprehensive information on the examination and the results.

Fig. 1 Elevated temperature application

Fig. 2 Tests

3.1 Effects of elevated temperature and waste fire clay ratio on compressive strength for fine aggregate replacement

In this section, while the amount of cement in the mixture was kept constant, the amount of fine aggregate was changed and its effect on the strength value of the mixture was investigated. For this purpose, CS tests were carried out according to ASTM C39/C39M(C39-12 2012) standards. The target could only be achieved by using test specimen lengths of 150 mm×300 mm. During the

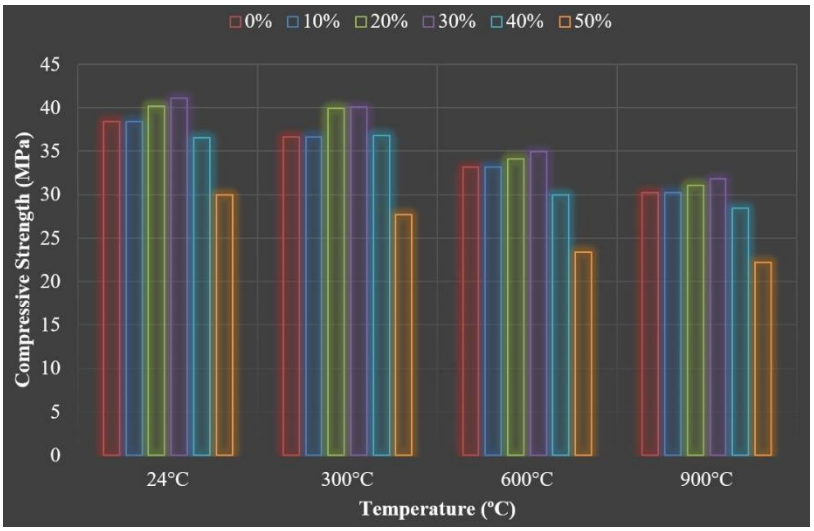

Fig. 3 Effects of elevated temperature and waste fire clay ratio on compressive strength for fine aggregate replacement

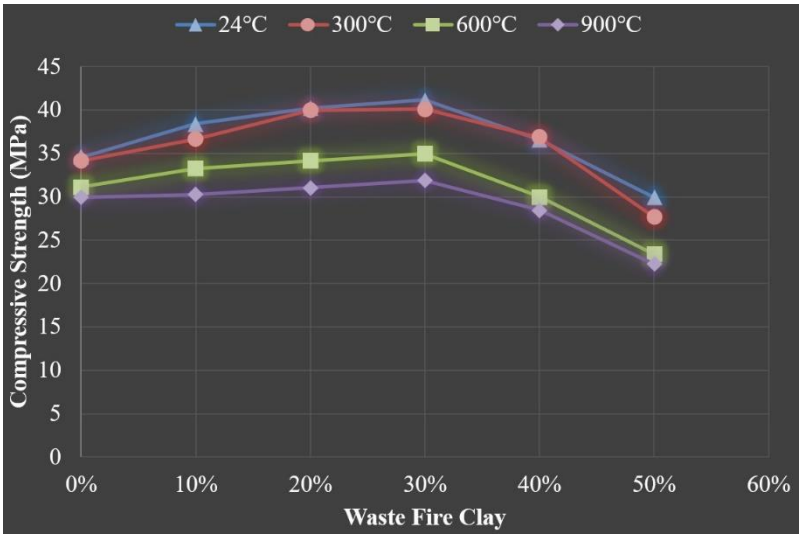

Fig. 4 Effects of elevated temperature and waste fire clay ratio on compressive strength for fine aggregate replacement

assessment, longitudinal constraint loads were applied to CS test specimens at a level that was appropriate for the incidence of specimen ruptures.

Based on the results of the CS experiments conducted at 24°C, the strength values were 34.57 MPa, 38.41 MPa, 40.21 MPa, 41.15 MPa, 36.57 MPa, and 29.96 MPa for the 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively as shown in Fig. 3. Increasing the proportion of WFC in the combination resulted in enhancements of 11.11%, 16.31%, 19.03%, and 5.79% in CS, but a reduction of 13.34% was noted for the ultimate mixture ratio (50%). It is observed that the strength increases as the ratio in the mixture increases up to 30%, and then (for 40% and 50%) it tends to decrease.

The experiment was repeated at 300°C, 600°C, and 900°C to enhance the temperature impact. The strength values obtained from the CS tests carried out at 300°C were 34.15 MPa, 36.68 MPa, 39.94 MPa, 40.11 MPa, 36.84 MPa and 27.69 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. The strength values for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios were 31.15 MPa, 33.22 MPa, 34.15 MPa, 34.98 MPa, 29.99 MPa, and 23.36 MPa, respectively, as determined by the CS experiments conducted at 600°C. The CS tests conducted at 900°C obtained the following strength values: 29.95 MPa, 30.26 MPa, 31.05 MPa, 31.86 MPa, 28.44 MPa, and 22.21 MPa for mixing ratios of 0%, 10%, 20%, 30%, 40%, and 50%, respectively. Analysis of the data indicates that strength rises at all temperature values with the addition of waste fire clay in the combination up to 30%, after which it declines at 40% and 50% concentrations.

Likewise, while keeping the amount of WFC in the mixture constant, the graph obtained as a result of increasing the temperature values to 24°C, 300°C, 600°C, and 900°C is given in Fig. 4. Accordingly, the strength values that were achieved as a consequence of the temperature increase were 34.57 MPa, 34.15 MPa, 31.15 MPa, and 29.95 MPa, respectively, even though the quantity of WFC was held constant at 0%. The strength values obtained with a constant WFC content of 10% at increasing temperatures were 38.41 MPa, 36.68 MPa, 33.22 MPa, and 30.26 MPa, respectively.

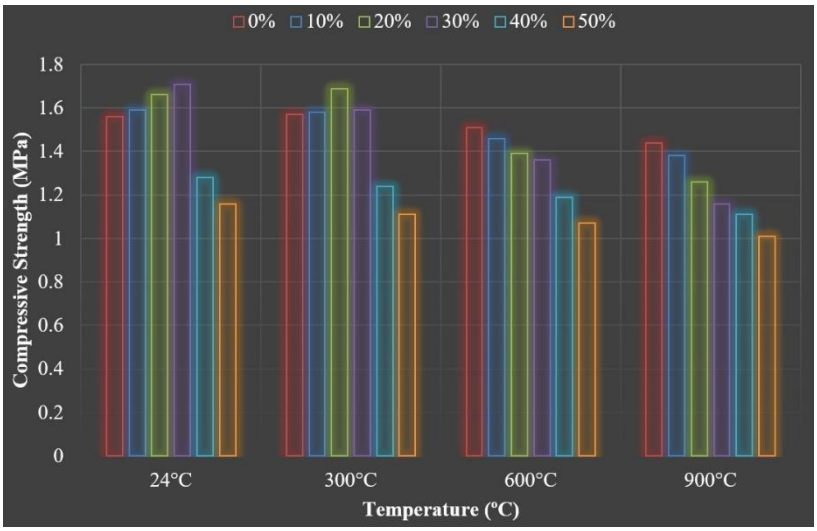

Fig. 5 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for fine aggregate replacement

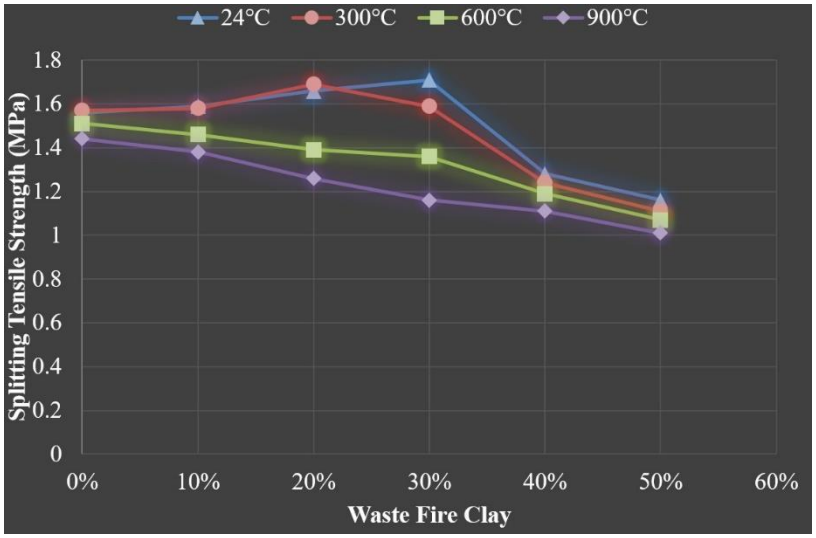

Fig. 6 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for fine aggregate replacement

For 20% waste fire clay, the strength values at various temperatures are 40.21 MPa, 39.94 MPa, 34.15 MPa, and 31.05 MPa. The strength values for waste fire clay at various temperatures are as follows: 30%: 41.15 MPa, 40.11 MPa, 34.98 MPa, 31.86 MPa; 40%: 36.57 MPa, 36.84 MPa, 29.99 MPa, 28.44 MPa; and 50%: 29.96 MPa, 27.69 MPa, 23.36 MPa, 22.21 MPa. To put it another way, strength levels decreased as the temperature increased.

3.2 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for fine aggregate replacement

In this part, the quantity of fine aggregate was altered and its impact on the combination's strength value was examined, while the amount of cement in the mixture remained constant. For this purpose, Splitting Tensile Strength tests were carried out according to ASTM 2017 (Concrete and Aggregates 2017) standards. Cylindrical samples with dimensions of 10×20 cm were used for STS testing.

Based on the results of the STS experiments conducted at 24°C, the strength values were 1.56 MPa, 1.59 MPa, 1.66 MPa, 1.71 MPa, 1.28 MPa, and 1.16 MPa for the 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively as shown in Fig. 5. Increasing the proportion of WFC in the combination resulted in enhancements of 1.92%, 6.41%, and 9.62% in concrete strength, but reductions of 17.95% and 25.64% were noted for the final mixture ratios of 40% and 50%, respectively. It is observed that the strength increases as the ratio in the mixture increases up to 30%, and then (for 40% and 50%) it tends to decrease.

The experiment was repeated at 300°C, 600°C, and 900°C to enhance the temperature impact. The STS tests conducted at 300°C produced the following strength values: 1.57 MPa, 1.58 MPa, 1.69 MPa, 1.59 MPa, 1.24 MPa, and 1.11 MPa for mixing ratios of 0%, 10%, 20%, 30%, 40%, and 50%, respectively. The strength values obtained from the STS tests performed at 600°C were obtained as 1.51 MPa, 1.46 MPa, 1.39 MPa, 1.36 MPa, 1.19 MPa and 1.07 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. 0%, 10%, 20%, 30%, 40%, and 50% mixing

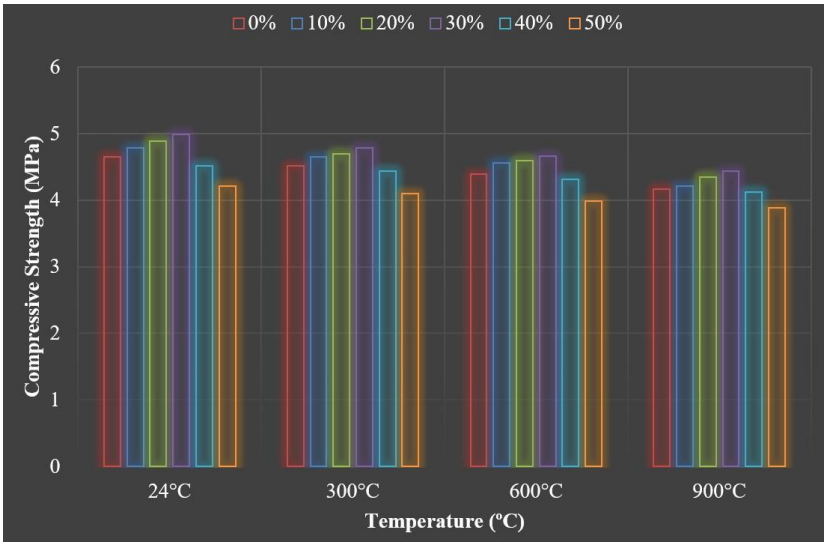

Fig. 7 Effects of elevated temperature and waste fire clay ratio on flexural strength for fine aggregate replacement

ratios resulted in strength values of 1.44 MPa, 1.38 MPa, 1.26 MPa, 1.16 MPa, 1.11 MPa, and 1.01 MPa, respectively, from CS experiments conducted at 900°C. When the results obtained here are examined, it is seen that the strength increases under all temperature values by increasing the amount of waste fire clay in the mixture up to 20%, and after that it tends to decrease for 30%, 40% and 50%.

Similarly, the graph obtained as a result of increasing the temperature values to 24°C, 300°C, 600°C, and 900°C while keeping the amount of WFC in the mixture constant is given in Fig. 6. Accordingly, while the amount of waste fire clay was kept constant at 0%, the strength values obtained as a result of the increase in temperature were found to be 1.56 MPa, 1.57 MPa, 1.51 MPa and 1.44 MPa, respectively. While the amount of WFC was kept constant at 10%, the strength values obtained as a result of increasing the temperature were found to be 1.59 MPa, 1.58 MPa, 1.46 MPa and 1.38 MPa, respectively. The strength values at varying temperatures for 20% WFC are 1.66 MPa, 1.69 MPa, 1.39 MPa, and 1.26 MPa, respectively. At varying temperatures, WFC strength values for 30%, 40%, and 50% are 1.71 MPa, 1.59 MPa, 1.36 MPa, and 1.16 MPa for 30%, 1.28 MPa, 1.24 MPa, 1.19 MPa, and 1.11 MPa for 40%, and 1.16 MPa, 1.11 MPa, 1.07 MPa, and 1.01 MPa for 50%. Stated differently, strength levels decreased as the temperature ascended.

3.3 Effects of elevated temperature and waste fire clay ratio on flexural tensile strength for fine aggregate replacement

This section examined the impact of varying the quantity of FA on the mixture's strength value while maintaining a constant amount of cement. For this purpose, FS tests were carried out according to ASTM 2016 (Concrete and Aggregates 2016). Test specimens with dimensions of 10×10×40 cm were subjected to flexural testing. Based on the results of the FS experiments conducted at 24°C, the strength values were 4.65 MPa, 4.78 MPa, 4.89 MPa, 4.99 MPa, 4.51 MPa, and 4.21 MPa for the 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively (Fig. 7). Increasing the proportion of WFC in the mixture resulted in strength enhancements of 2.80%, 5.16%, and 7.31%. Conversely, a reduction in strength of 3.01% and 9.46% was noted for the final mixture ratios of 40% and 50%, respectively. It has been noted that the potency of the mixture increases as the ratio increases up to 30%, and then it tends to diminish (for 40% and 50%).

This experiment was conducted at 300°C, 600°C, and 900°C when the temperature effect was increased. According to the results of the FS tests that were carried out at a temperature of 300°C, the values of strength that were obtained were 4.51 MPa, 4.65 MPa, 4.69 MPa, 4.78 MPa, 4.44 MPa, and 4.1 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. Results from FS tests at 600°C showed strength values of 4.39, 4.56, 4.59, 4.66, 4.31, and 3.99 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios. The strength values obtained from the FS tests performed at 900°C were obtained as 4.16 MPa, 4.21 MPa, 4.35 MPa, 4.44 MPa, 4.12 MPa and 3.88 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. Upon examination of the results obtained here, it is evident that the strength increases across all temperature ranges when the quantity of WFC in the mixture is increased to 30%. Subsequently, the strength diminishes for 40% and 50%.

Similarly, Fig. 8 illustrates the graph that is produced when the temperature values are raised to 24℃, 300°C, 600°C, and 900°C while maintaining a constant quantity of WFC in the mixture. Accordingly, while the amount of WFC was kept constant at 0%, the strength values obtained as a result of the increase in temperature were found to be 4.65 MPa, 4.51 MPa, 4.39 MPa and 4.16 MPa, respectively. The strength values attained as a consequence of the increase in temperature were 4.78 MPa, 4.65 MPa, 4.56 MPa, and 4.21 MPa, when the quantity of WFC was maintained at 10%. For 20% WFC, the strength values are 4.89 MPa, 4.69 MPa, 4.59 MPa, and 4.35 MPa at varying temperatures. Strength values, at various temperatures, for

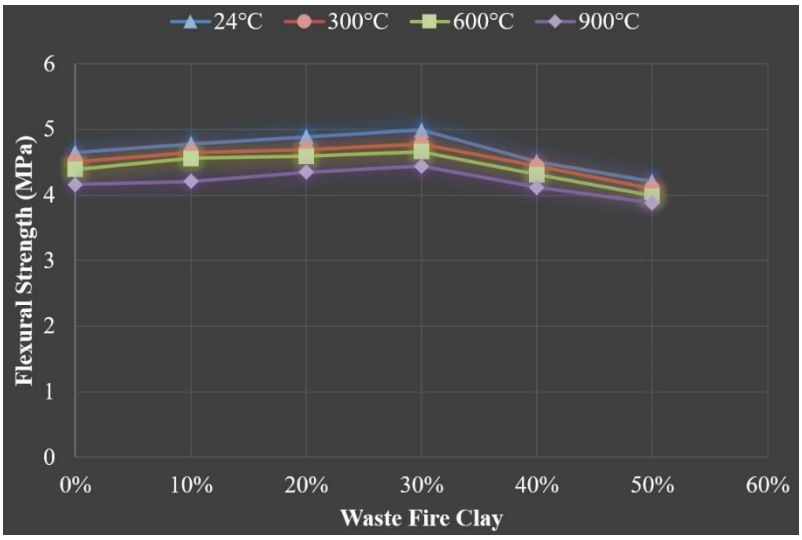

Fig. 8 Effects of elevated temperature and waste fire clay ratio on flexural strength for fine aggregate replacement

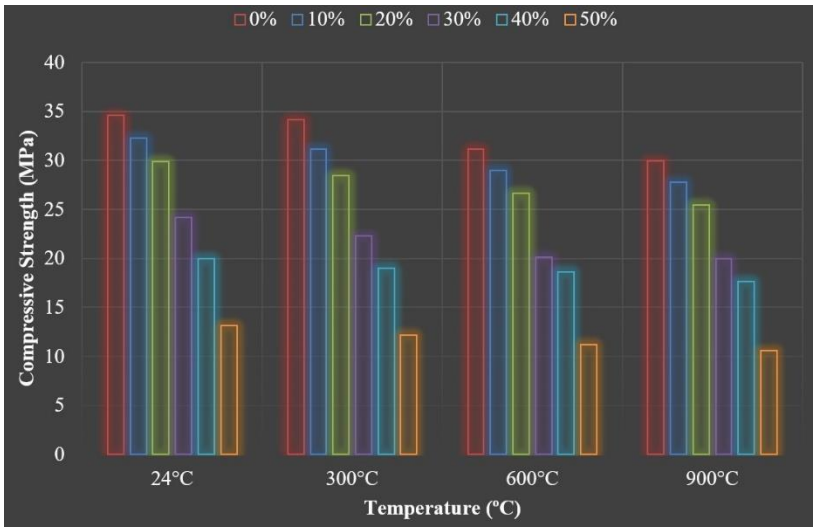

Fig. 9 Effects of elevated temperature and waste fire clay ratio on compressive strength for cement replacement

30%, 40%, and 50% WFC are: 4.99 MPa, 4.78 MPa, 4.66 MPa, and 4.44 MPa for 30%; 4.51 MPa, 4.44 MPa, 4.31 MPa, and 4.12 MPa for 40%; and 4.21 MPa, 4.1 MPa, 3.99 MPa, and 3.88 MPa. Another way of putting it is that the rise in temperature led to a fall in the levels of strength.

3.4 Effects of elevated temperature and waste fire clay ratio on compressive strength for cement replacement

In this section, while the amount of fine aggregate in the mixture was kept constant, the amount of cement was changed and its effect on the CS strength value of the mixture was investigated. According to the results of the CS tests that were carried out at a temperature of 24°C, the strength values that were obtained were 34.57 MPa, 32.24 MPa, 29.85 MPa, 24.15 MPa, 19.96 MPa, and 13.11 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. When the quantity of WFC in the mixture was increased, it was seen that the strength of the concrete decreased by 6.74%, 13.65%, 30.14%, 42.26%, and 62.08% respectively. Experiments were carried out at temperatures of 300°C, 600°C Celsius, and 900°C, when the temperature impact was amplified. The strength values that were obtained from the CS tests that were carried out at a temperature of 300°C were as follows: 34.15 MPa, 31.16 MPa, 28.44 MPa, 22.33 MPa, 18.96 MPa, and 12.16 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. For the 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, the strength values derived from the CS experiments conducted at 600°C were 31.15 MPa, 28.99 MPa, 26.67 MPa, 20.13 MPa, 18.58 MPa, and 11.16 MPa, respectively. During the CS tests that were conducted at 900°C, the values of strength that were obtained were as follows: 29.95 MPa, 27.77 MPa, 25.41 MPa, 19.96 MPa, 17.65 MPa, and 10.56 MPa for respective mixing ratios of 0%, 10%, 20%, 30%, 40%, and 50%. When the results obtained here are examined, it is concluded that the strength decreases under all temperature values by increasing the amount of WFC in the mixture.

Similarly, the graph obtained as a result of increasing the temperature values to 24°C, 300°C, 600°C, and 900°C

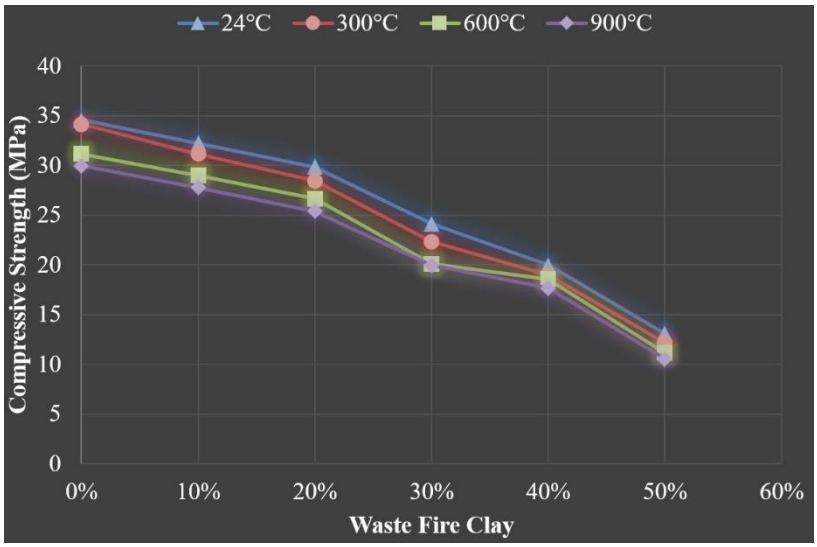

Fig. 10 Effects of elevated temperature and waste fire clay ratio on compressive strength for cement replacement

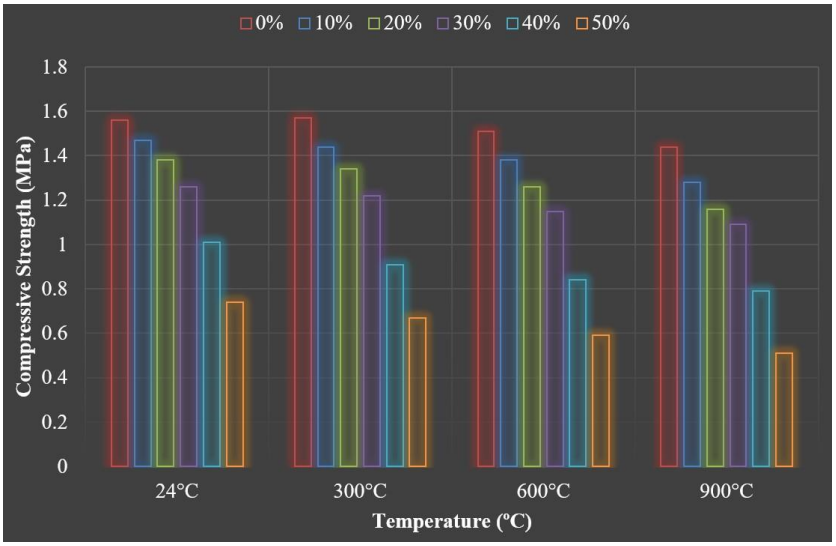

Fig. 11 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for cement replacement

while keeping the amount of WFC in the mixture constant is given in Fig. 10. Accordingly, the strength values that were produced as a consequence of the rise in temperature were determined to be 34.57 MPa, 34.15 MPa, 31.15 MPa, and 29.95 MPa, respectively. This was the case even though the quantity of WFC was maintained at 0% throughout the experiment. In spite of the fact that the percentage of WFC was maintained at 10% throughout the experiment, the values of strength that were acquired as a consequence of the rise in temperature were discovered to be 32.24 MPa, 31.16 MPa, 28.99 MPa, and 27.77 MPa, individually. The strength values at different temperatures for 20% WFC are 29.85 MPa, 28.44 MPa, 26.67 MPa and 25.41 MPa, respectively. The strength values at different temperatures for 30%, 40% and 50% waste fire clay were obtained as 24.15 MPa, 22.33 MPa, 20.13 MPa and 19.96 MPa for 30%, 19.96 MPa, 18.96 MPa, 18.58 MPa and 17.65 MPa for 40%, and finally 13.11 MPa, 12.16 MPa, 11.16 MPa and 10.56 MPa for 50%, respectively. That is, the strength values decreased as a result of the rise in temperature.

3.5 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for cement replacement

In this section, it was noted that the affect of elevated temperature and WFC ratio on the STS of cement replacement. As can be observed in Fig. 11, the strength values that were obtained from STS tests that were held at 24°C were 1.56 MPa, 1.47 MPa, 1.38 MPa, 1.26 MPa, 1.01 MPa, and 0.74 MPa for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, respectively. As the proportion of WFC in the mixture was increased, the strength of the concrete was found to drop by 5.77%, 11.54%, 19.23%, 35.26%, and 52.5%, respectively. It is observed that the strength tends to decrease with increasing the ratio in the mixture.

When the temperature effect was increased—300°C, 600°C, and 900°C—the same experiment was performed. The STS tests that were carried out at a temperature of 300°C results in the following strength values: 1.57 MPa, 1.44 MPa, 1.34 MPa, 1.22 MPa, 0.91 MPa, and 0.67 MPa

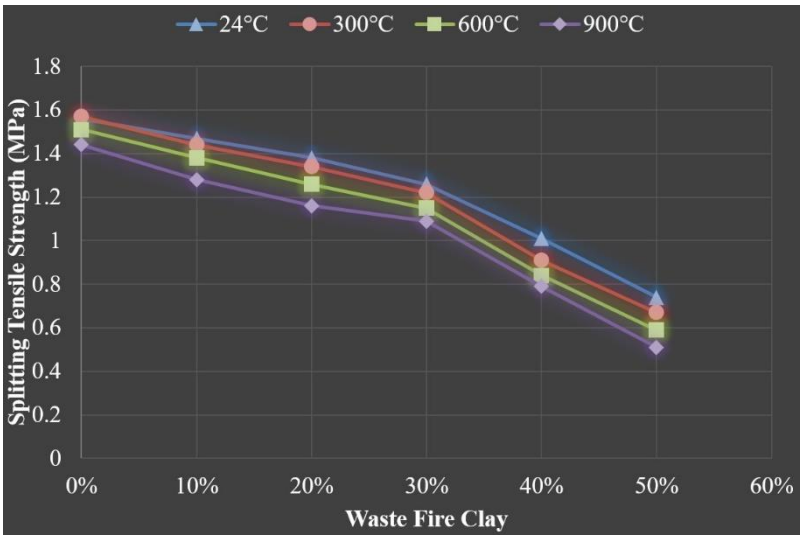

Fig. 12 Effects of elevated temperature and waste fire clay ratio on splitting tensile strength for cement replacement

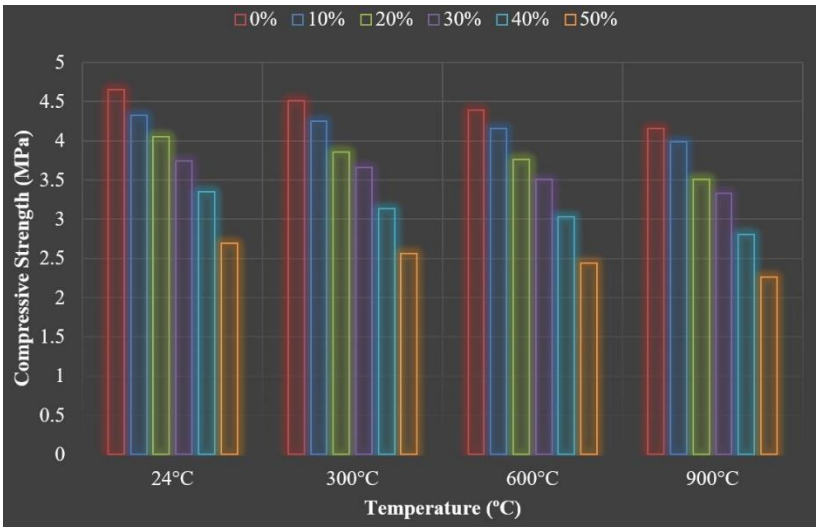

Fig. 13 Effects of elevated temperature and waste fire clay ratio on flexural strength for cement replacement

for a mixing ratio of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. At 600°C, the STS tests yielded strength values of 1.51 MPa, 1.38 MPa, 1.26 MPa, 1.15 MPa, 0.84 MPa, and 0.59 MPa for mixing ratios of 0%, 10%, 20%, 30%, 40%, and 50%, respectively. At 900°C, the STS experiments yielded strength values of 1.44 MPa, 1.28 MPa, 1.16 MPa, 1.09 MPa, 0.79 MPa, and 0.51 MPa for mixing ratios of these percentage, respectively. When the results obtained here are examined, it is seen that the strength tends to decrease under all temperature values by increasing the amount of WFC in the mixture.

Similarly, the graph obtained as a result of increasing the temperature values to 24°C, 300°C, 600°C, and 900°C while keeping the amount of WFC in the mixture constant is given in Fig. 12. Accordingly, while the amount of WFC was kept constant at 0%, the strength values obtained as a result of the increase in temperature were found to be 1.56 MPa, 1.57 MPa, 1.51 MPa and 1.44 MPa, respectively. While the amount of WFC was kept constant at 10%, the strength values obtained as a result of the increase in temperature were found to be 1.47 MPa, 1.44 MPa, 1.38 MPa and 1.28 MPa, respectively. Accordingly, the strength values for 20% waste fire clay at various temperatures are 1.38 MPa, 1.34 MPa, 1.26 MPa, and 1.16 MPa. The strength values at different temperatures for 30%, 40% and 50% waste fire clay were obtained as 1.26 MPa, 1.22 MPa, 1.15 MPa and 1.09 MPa for 30%, 1.01 MPa, 0.91 MPa, 0.84 MPa and 0.79 MPa for 40% and finally 0.74 MPa, 0.67MPa, 0.59 MPa and 0.51 MPa for 50%, respectively. In other words, the increase in temperature caused a decrease in strength values.

3.6 Effects of elevated temperature and waste fire clay ratio on flexural strength for cement replacement

The impact of WFC Ratio and elevated temperature on FS for cement replacement was examined. Fig. 13 illustrates that the strength values derived from the FS tests conducted at 24°C were 4.65 MPa, 4.32 MPa, 4.05 MPa, 3.74 MPa, 3.35 MPa, and 2.69 MPa for mixing ratios of 0%, 10%, 20%, 30%, 40%, and 50%, respectively. By increasing the amount of WFC in the mixture, a decrease of

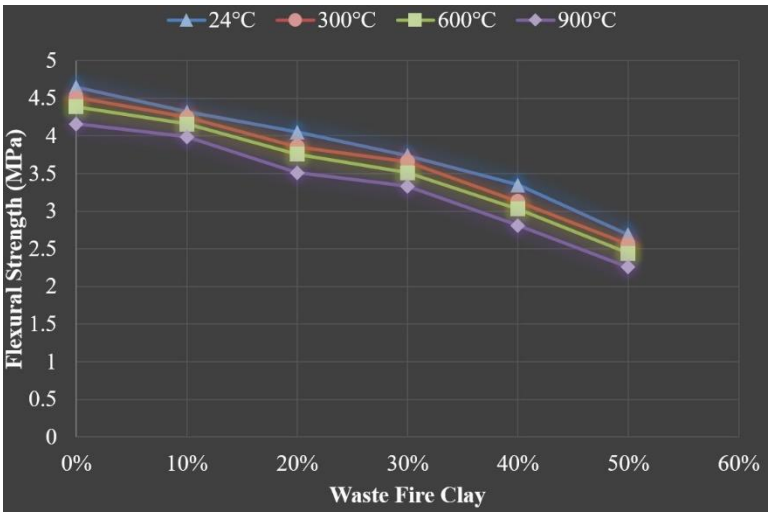

Fig. 14 Effects of elevated temperature and waste fire clay ratio on flexural strength for cement replacement

7.10%, 12.90%, 19.57%, 27.96% and 42.15% in the strength of concrete was observed. As the percentage in the mixture increases, it has been shown that the strength tends to decrease.

When the temperature effect was increased—300°C, 600°C, and 900°C—the same experiment was performed. Strength values for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios were 4.51 MPa, 4.25 MPa, 3.86 MPa, 3.66 MPa, 3.13 MPa, and 2.56 MPa, respectively, based on FS tests conducted at 300°C. For 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios, the corresponding strength values from the STS tests conducted at 600°C were 4.39 MPa, 4.16 MPa, 3.76 MPa, 3.51 MPa, 3.03 MPa, and 2.44 MPa. According to the STS tests conducted at 900°C, the strength values for 0%, 10%, 20%, 30%, 40%, and 50% mixing ratios were 4.16 MPa, 3.99 MPa, 3.51 MPa, 3.33 MPa, 2.81 MPa, and 2.26 MPa, respectively. When the results obtained here are examined, it is seen that the strength tends to decrease under all temperature values by increasing the amount of WFC in the mixture.

Correspondingly, the graph resulting from elevating the temperature values to 24°C, 300°C, 600°C, and 900°C, while maintaining a constant quantity of waste fire clay in the combination, is shown in Fig. 14. Accordingly, while the amount of WFC was kept constant at 0%, the strength values obtained as a result of the increase in temperature were found to be 4.65 MPa, 4.51 MPa, 4.39 MPa and 4.16 MPa, respectively.

With the proportion of WFC maintained at 10%, the strength values recorded due to the temperature rise were 4.32 MPa, 4.25 MPa, 4.16 MPa, and 3.99 MPa, respectively. The strength values at different temperatures for 20% WFC are 4.05 MPa, 3.86 MPa, 3.76 MPa and 3.51 MPa, respectively. For 30%, 40%, and 50% WFC, the strength values at various temperatures were 3.74 MPa, 3.66 MPa, 3.51 MPa, and 3.33 MPa for 30%, 3.35 MPa, 3.13 MPa, 3.03 MPa, and 2.81 MPa for 40%, and 2.69 MPa, 2.56 MPa, 2.44 MPa, and 2.26 MPa for 50%, respectively. In other words, the increase in temperature caused a decrease in the strength values. The decreasing trend is seen in detail in Fig. 14.

4. Discussion of the results

FA was mixed with WFC in weight ratios of 0%, 10%, 20%, 30%, 40%, and 50%, and exposed to three distinct high temperatures (300°C, 600°C, and 900°C), revealing that elevated temperatures decreased the CS of the concrete. The findings that were obtained were found to be in agreement with the research that was carried out in the literature. This is caused, in part, by the concrete losing water (free water, interlayer water, and chemically mixed water) all of which are essential to the concrete matrix's strength and cohesiveness. (Abdullah and Mohammed 2023). The heat expansion of concrete was cited as an additional explanation for the phenomenon. Internal strains and fractures that damage the structure of the concrete are known to be caused by thermal expansion, which is a well-known phenomenon (Abdullah and Mohammed 2023). There is a third argument, which is that research has shown the chemical breakdown of some components of concrete, such as calcium hydroxide and calcium silicate hydrate. Debieb and Kenai (2008) showed that this strength reduction was due to the high water absorption of recycled fine aggregates. A reduction in the characteristics of concrete has been shown to be the result of this degradation (Guo and Shi 2011, Kuehnen *et al.* 2022, Abdullah and Mohammed 2023). For cement replacement with WFC, it was observed similar results. According to the findings of a research that investigated the impact of substituting 5%-20% of cement with burnt clay on that parameter, it was found that the pozzolanic activity of the addition led to an increase in mechanical strength in every single instance (Poon *et al.* 2001, Asensio *et al.* 2020).

5. Micro structural analysis

5.1 Field Emission Scanning Electron Microscope (FE-SEM) analysis

FE-SEM analysis uses field emission as the electron source: This produces a very fine electron beam, enabling

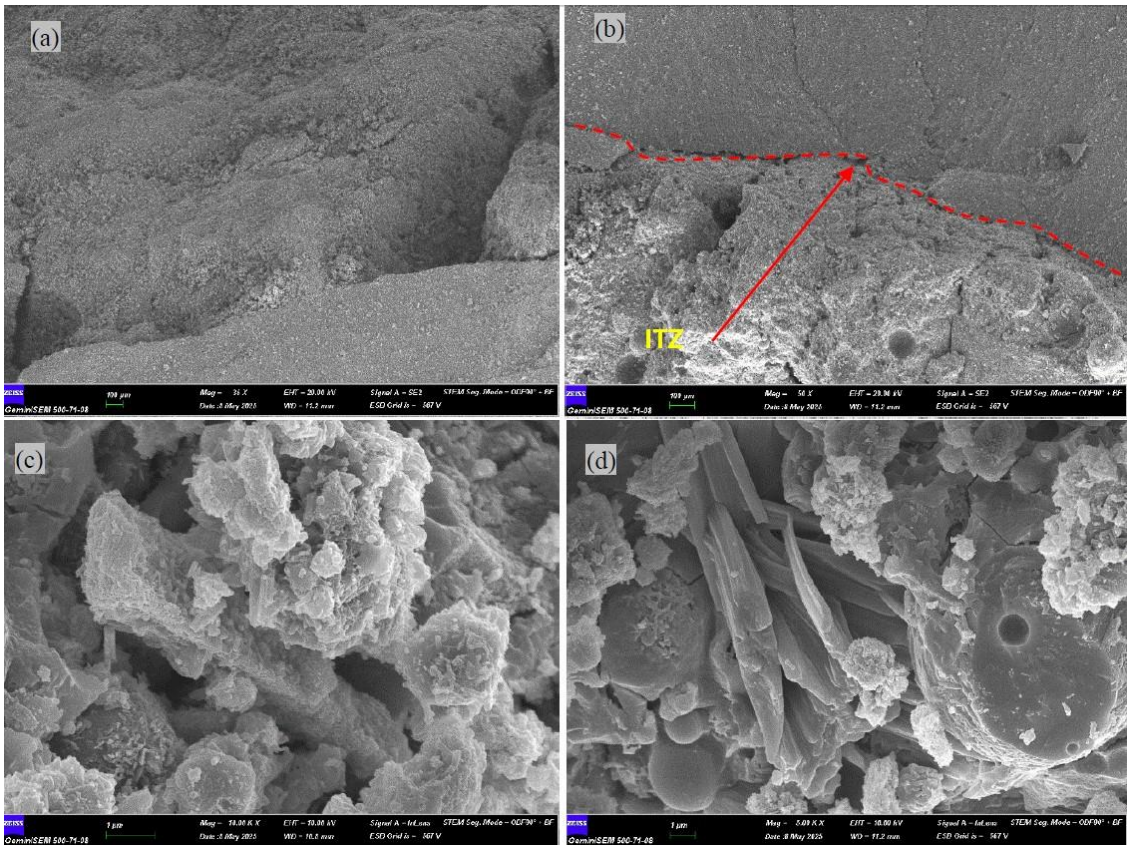

Fig. 15 FE-SEM analysis results 1

clearer, higher-resolution images to be obtained. This allows for a more detailed representation of surface morphology, making it ideal for nano-level material analysis. Even sensitive samples can be examined without damage.

In general, clay addition has accelerated reactions in some areas, promoting the formation of a dense structure, while in other areas it has caused porosity and micro-cracks. The magnification ratio in Fig. 15(a)) is 34*x*. This image shows the general morphology of the surface. Significant heterogeneity and microcrack-like separations are observed on the surface. The clay addition may have resulted in local voids and weak bond regions due to an inhomogeneous mixture. This could be attributed to low workability or inadequate mixing. Fig. 15(b)) shows an image with a magnification of 98*x*. Here, the surface has been examined in greater detail, and microcracks and transitional structures are more clearly visible. Cracks are present in the upper region, while the lower region features a dense and porous structure. This image may indicate microcracks developed due to thermal stresses during drying or weak gel bonds. The excessive porosity may have negative effects on strength. A distinct Interfacial Transition Zone (ITZ) between the geopolymer matrix and an adjacent aggregate particle is observed as shown in Fig. 15(b). A visibly porous and heterogeneous microstructure with microcrack propagation paths is characteristic of this zone. The presence of clay, probably due to inadequate bonding between the calcium silicate hidarete (C-S-H) gel and the aggregate surface, appears to exacerbate the heterogeneity of the ITZ. This observation is consistent with previous findings that the ITZ typically exhibits reduced mechanical integrity due to reduced packing density and increased porosity (Franus *et al.* 2015, Zhang and Li 2011). The apparent microcracking in this region indicates that the ITZ may act as a weak zone and could have a significant impact on the overall mechanical performance and durability of the composite, particularly under tensile or cyclic loading conditions. Fig. 15(c)) Image, magnification 1808*x*. At high magnification, amorphous structures that have not crystallized are visible, along with particles aggregated in agglomerates. This image indicates that the C-S-H or C-H gel structures have not fully developed and that partially reacted clay particles are still present in the system. Microporosity is notable. Fig. 15(d)) shows an image with a magnification of 1808*x*. Large crystalline needle-like structures with fiber-like features are prominent. Dense small particles are present around these structures. Such needle-like crystals typically indicate ettringite-like structures. Some minerals in the clay (e.g., halloysite) can form these structures. Different hydration products are observed in the reaction environment, resulting in a complex microstructure.

It can be seen that the matrix has a generally dispersed and loosely bound structure in the 250*x* magnified (20 μm scale) FE-SEM image shown in Fig. 16(a). Significant voids and unbound fine particles are present throughout the matrix. This indicates that the low level of clay replacement is insufficient to ensure adequate microstructural integrity. The structure observed in Fig. 16(b) (500*x* magnification,

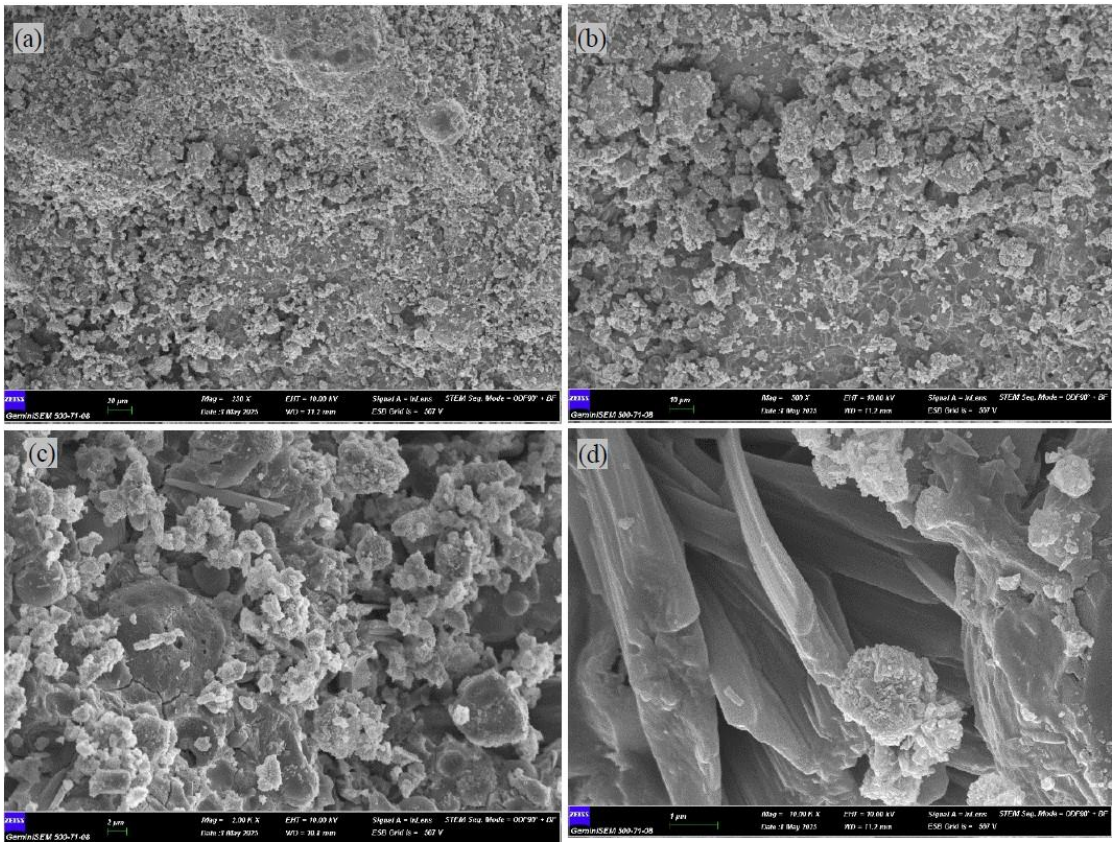

Fig. 16 FE-SEM analysis results 2

10 μm scale) shows a more compact morphology when compared to the previous image. However, granular structures are still evident and there are some deficiencies in the homogeneity of the binder phase. This suggests that the addition of a certain amount of clay improves the binder phase, but that increased clay content may negatively affect the hydration process. Tightly bound, amorphous and small gel-like structures are observed within the matrix in the image shown in Fig. 16(c) at 2900*x* magnification (2 μm scale). These structures indicate the presence of hydration products similar to C-S-H phases. In addition, small diameter micropores are observed in the structure, but these voids are generally considered to be within acceptable limits. Needle-like crystalline structures are noticeable in the image in Fig. 16(d) at 10,000*x* magnification (1 μm scale). These structures indicate the formation of ettringite-like hydration products, and fibrous morphologies associated with small particles are also present around them. Excessive clay content can promote the formation of such crystalline structures, but this can have negative mechanical consequences by increasing brittleness and irregularity in the microstructure. In general, findings from SEM images show that the microstructure evolves as the chamotte replacement increases. At low replacement levels (0-10%), porous and loosely bound structures are prominent. At medium replacement levels (20-30%), the microstructure becomes denser and the development of gel phases is observed. Needle-like crystals seen at high magnification indicate the presence of ettringite-type hydration products. These are beneficial at certain ratios but can cause the structure to become brittle at 40-50% replacement.

5.2 Energy DISPERSIVE X-ray Spectroscopy (EDX) analysis

The EDX spectrum shown in Fig. 17 shows oxygen (O) as the most prominent peak, indicating the presence of hydrated phases such as C-S-H and C-A-S-H gels. The significant detection of silicon (Si), which is a major constituent of both the C-S-H and C-A-S-H structures, suggests the formation of aluminosilicate gel networks, which is consistent with the incorporation of fire clay and/or reactive silica containing phases. The presence of aluminium (Al) further supports the development of C-A-S-H phases and confirms the pozzolanic reactivity of the clay component. Moderate levels of calcium (Ca)-despite the partial replacement of cement-indicate the continued formation of C-S-H type phases and possibly ettringite-like structures, particularly in regions with needle-like morphologies observed in the SEM images. In addition, the detection of sodium (Na) and potassium (K) can be attributed to the natural alkali content of the clay or residual cement phases. These alkaline elements are known to facilitate geopolymerisation processes by enhancing ion mobility and gel polymerisation. The presence of iron (F) is probably due to the inherent mineralogical composition of the clay or trace impurities. Although not a primary binding element, it may influence long-term durability. Finally, the low detection of magnesium (Mg) indicates its limited role,

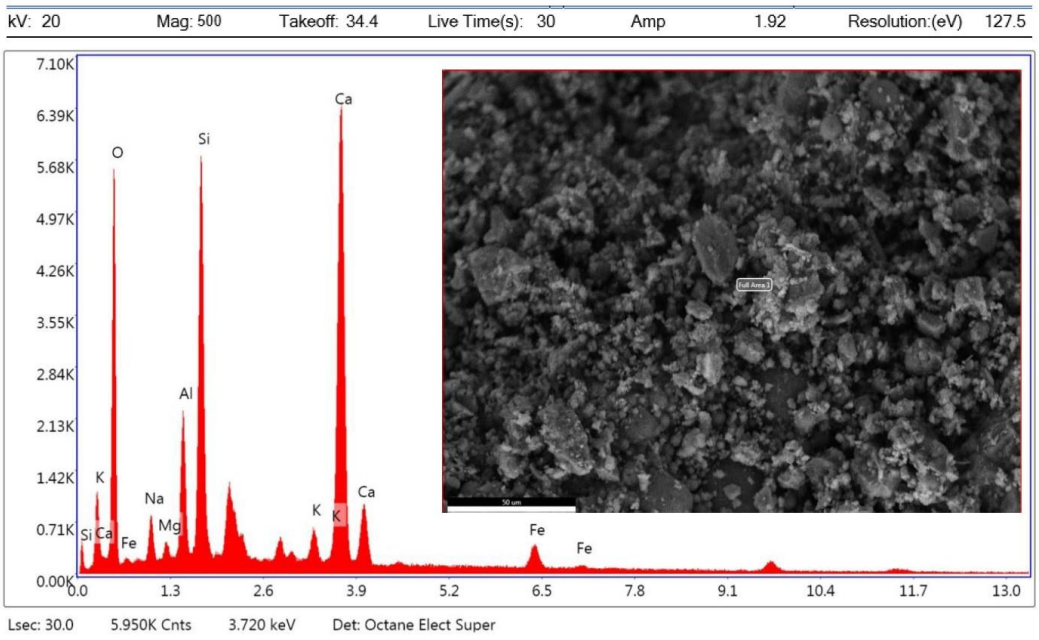

Fig. 17 EDX analysis of area 1

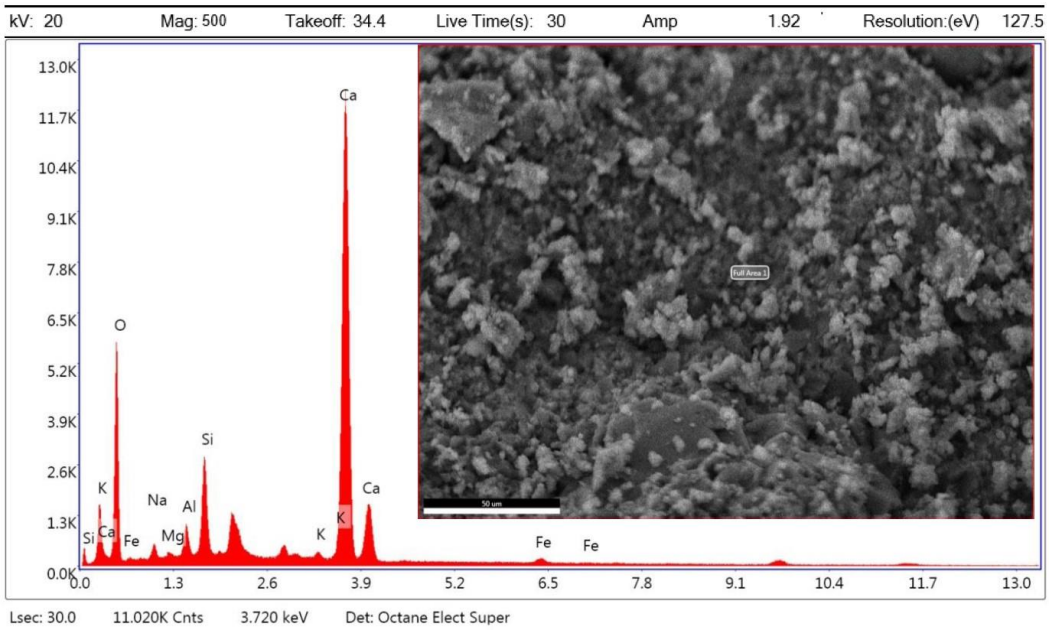

Fig. 18 EDX analysis of area 2

which may be associated with minor phases of the C-A-S-H type or may represent a trace impurity in the raw materials**.**

In the first region of Fig. 17, clay substitution corresponds to distinct areas and supports the intensive formation of gel phases such as C-A-S-H/C-S-H with high Si and Al contents. In contrast, the second region in Fig. 18 represents a microstructure that is similar to that of cement and is characterised by a higher Ca content and the dominance of the classical C-S-H phases. This indicates that the clay substitution can locally affect the microstructure in a different way, in particular by introducing a heterogeneity in the composition and distribution of the binder phases

When EDX analyses from two different regions were compared, significant differences in elemental composition were observed. This statistical analysis is shown in Fig. 19. From the results of the EDX analysis, significant changes in the chemical composition of the microstructure have been observed in mixtures where clay has been a substitute for cement. It has been observed that the Si and Al ratios increase with clay substitution, while the Ca content decreases. This indicates that the C-S-H phases are partially replaced by N-A-S-H or C-A-S-H gel phases. The observed differences in element concentrations between different regions are an indication that the clay is not homogeneously distributed in the matrix and may cause local chemical variations in the microstructure.

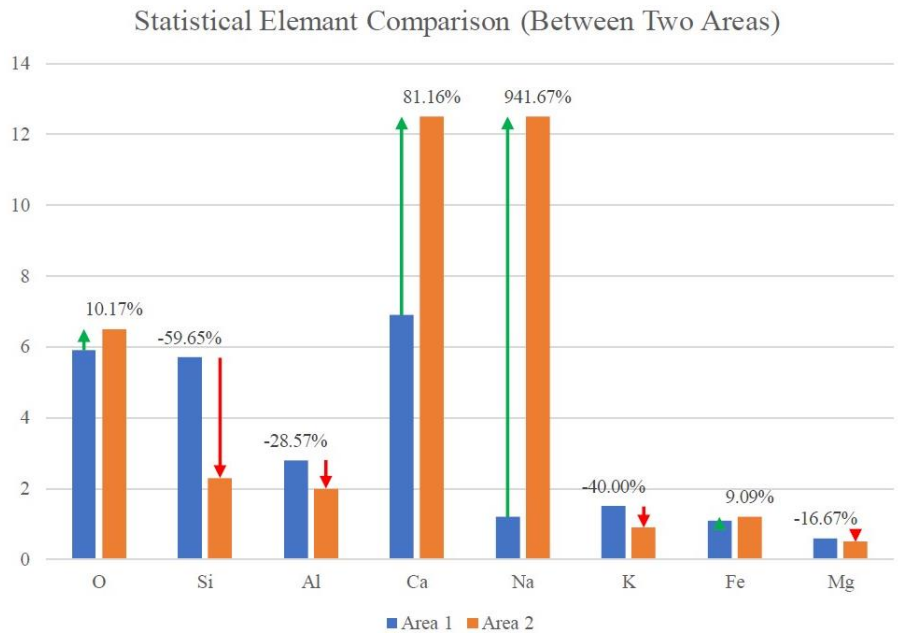

Fig. 19 Statistical comparison in EDX analysis

6. Conclusions

In this investigational study, the influence of different WFC percentages as a replacement for FA and cement were examined. For that reason, WFC was replaced by the use of the FA and cement. These replacement percentages were selected as 0%, 10%, 20%, 30%, 40% and 50%. Additionally, the samples were exposed to three specific high temperatures—300°C, 600°C, and 900°C—before testing. The following is a list of the results that were obtained.

- As a result of replacing WFC with the use of FA, there was an increase in the CS values of the mix by up to 30%. The maximum CS amount was found to be 41.15 MPa. A decrease in the amount of CS was observed for the 40% and 50% mixture.This trend in CS results was found to be valid for all temperature -24°C, 300°C, 600°C, and 900°C- values.
- When cement was used in place of WFC, the mix's CS values increased by as much as 20 %. It was found that the 30%, 40%, and 50% mixtures had less CS. It is observed that concrete strength decreases with increasing temperature.
- On examination of the STS values of the concrete mixture, it was observed that the strength increased to 1.71 MPa as a consequence of the replacement with fine aggregate up to 30%, and subsequently tended to decrease. On the other hand, after replacing 20% of the concrete mixture with cement, the STS values climbed to 1.38 MPa and thereafter decreased.
- FS findings revealed a concrete FS value of 4.99 MPa, a 30% change, and a lowering trend for additional values (40% and 50%). However, the FS values increased to 4.05 MPa and then decreased as a consequence of replacing 20% of the concrete mixture with cement.
- Fireclay substitution was found to be a significant contributor to the microstructural development in FE-SEM analyses. At low rates of substitution, the structure is porous and irregular, whereas at 30% substitution, gel-like phases develop and the microstructure becomes more dense. Needle-like crystals observed at high magnification indicate ettringite-like formations. However, excessive accumulation of these crystals can lead to brittleness in the microstructure at replacement ratios of 40% and above. These findings suggest that the optimum clay replacement ratio is critical to the mechanical strength and durability of the material..
- From the results of the EDX analysis, significant changes in the chemical composition of the microstructure have been observed in mixtures where clay has been a substitute for cement. It has been observed that the Si and Al ratios increase with clay substitution, while the Ca content decreases. This indicates that the C-S-H phases are partially replaced by C-A-S-H gel phases. The observed differences in element concentrations between different regions are an indication that the clay is not homogeneously distributed in the matrix and may cause local chemical variations in the microstructure.

Acknowledgement

The authors are thankful for the financial support provided for this research by the Deanship of Scientific Research at King Khalid University, Abha, Saudi Arabia, through Large Groups RGP2/539/46.

References

Abdullah, A.H. and Mohammed, S.D. (2023), "Effect of lightweight expanded clay aggregate as partial replacement of

coarse aggregate on the mechanical properties of fire-exposed concrete", *J. Mech. Behav. Mater.*, **32**(1), 20220299. https://doi.org/10.1515/jmbm-2022-0299.

Abdullah, A.H. and Mohammed, S.D. (2023), "The fire effect on the performance of reinforced concrete beams with partial replacement of coarse aggregates by expanded clay aggregates", *Eng. Technol. Appl. Sci. Res.*, **13**(6), 12220-12225. https://doi.org/10.48084/etasr.6412.

Aliabdo, A.A., Abd-Elmoaty, A.E.M. and Hassan, H.H. (2014), "Utilization of crushed clay brick in concrete industry", *Alex. Eng. J.*, **53**(1), 151-168. https://doi.org/10.1016/j.aej.2013.12.003.

Anjum, F., Ghaffar, A., Jamil, Y. and Majeed, M.I. (2019), "Effect of sintering temperature on mechanical and thermophysical properties of biowaste-added fired clay bricks", *J. Mater. Cycl. Waste Manage.*, **21**, 503-524. https://doi.org/10.1007/s10163-018-0810-x.

Asensio, E., Medina, C., Frías, M. and de Rojas, M.I.S. (2020), "Fired clay-based construction and demolition waste as pozzolanic addition in cements. Design of new eco-efficient cements", *J. Clean. Prod.*, **265**, 121610. https://doi.org/10.1016/j.jclepro.2020.121610.

Baspinar, M.S., Demir, I. and Orhan, M. (2010), "Utilization potential of silica fume in fired clay bricks", *Waste Manage. Res.*, **28**(2), 149-157. https://doi.org/10.1177/0734242X09104385.

Bhatnagar, J. and Goel, R. (2002), "Thermal changes in clay products from alluvial deposits of the Indo-Gangetic plains", *Constr. Build. Mater.*, **16**(2), 113-122. https://doi.org/10.1016/S0950-0618(01)00031-9.

Bidoung, J., Pliya, P., Meukam, P., Noumowé, A. and Beda, T. (2016), "Behaviour of clay bricks from small-scale production units after high temperature exposure", *Mater. Struct.*, **49**, 4991-5006. https://doi.org/10.1617/s11527-016-0838-0.

Bidoung, J.C., Mpoung, L.A., Mbey, J.A. and Meva'a, J.R.L. (2023), "Experimental and numerical study of mechanical behaviour of fired clay bricks after exposure to high temperatures", *J. Miner. Mater. Character. Eng.*, **11**(5), 143-160. https://doi.org/10.4236/jmmce.2023.115012.

C39-12, A. (2012), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA,

Chindaprasirt, P., Srisuwan, A., Saengthong, C., Lawanwadeekul, S. and Phonphuak, N. (2021), "Synergistic effect of fly ash and glass cullet additive on properties of fire clay bricks", *J. Build. Eng.*, **44**, 102942. https://doi.org/10.1016/j.jobe.2021.102942.

Concrete, A.I.C.C.o. and Aggregates, C. (2016), Standard Test Method for Flexual Strength of Concrete (using Simple Beam with Center-point Loading) 1, ASTM International.

Concrete, A.I.C.C.o. and Aggregates, C. (2017), Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens 1, ASTM International.

Cultrone, G., Sebastián, E., Elert, K., De la Torre, M.J., Cazalla, O. and Rodriguez-Navarro, C. (2004), "Influence of mineralogy and firing temperature on the porosity of bricks", *J. Eur. Ceram. Soc.*, **24**(3), 547-564. https://doi.org/10.1016/S0955-2219(03)00249-8.

Debieb, F. and Kenai, S. (2008), "The use of coarse and fine crushed bricks as aggregate in concrete", *Constr. Build. Mater.*, **22**(5), 886-893. https://doi.org/10.1016/j.conbuildmat.2006.12.013.

Dhanalakshmi, G. and Umamaheshwaran, V. (2015), "Use of fire clay as a partial replacement in concrete", *Int. J. Eng. Res. Technol. (IJERT)*, **4**(4), 451-455.

Franus, W., Panek, R. and Wdowin, M. (2015), "SEM investigation of microstructures in hydration products of portland cement", *2nd International Multidisciplinary Microscopy and Microanalysis Congress: Proceedings of InterM*, October.

Ge, Z., Wang, Y., Sun, R., Wu, X. and Guan, Y. (2015), "Influence of ground waste clay brick on properties of fresh and hardened concrete", *Constr. Build. Mater.*, **98**, 128-136. https://doi.org/10.1016/j.conbuildmat.2015.08.100.

Gencel, O. (2015), "Characteristics of fired clay bricks with pumice additive", *Energy Build.*, **102**, 217-224. https://doi.org/10.1016/j.enbuild.2015.05.031.

Gualtieri, M.L., Gualtieri, A.F., Gagliardi, S., Ruffini, P., Ferrari, R. and Hanuskova, M. (2010), "Thermal conductivity of fired clays: Effects of mineralogical and physical properties of the raw materials", *Appl. Clay Sci.*, **49**(3), 269-275. https://doi.org/10.1016/j.clay.2010.06.002.

Guo, Z. and Shi, X. (2011), *Experiment and Calculation of Reinforced Concrete at Elevated Temperatures*, Elsevier.

Isah, B.W. (2014), "Effect of coconut shell ash on properties of fired clay brick", *J. Civil Eng. Environ. Technol.*, **1**(6), 7-11.

Joyklad, P., Nawaz, A. and Hussain, Q. (2018), "Effect of fired clay brick aggregates on mechanical properties of concrete", *Suranaree J. Sci. Technol.*, **25**(4), 349.

Kadir, A.A. and Mohajerani, A. (2015), "Effect of heating rate on gas emissions and properties of fired clay bricks and fired clay bricks incorporated with cigarette butts", *Appl. Clay Sci.*, **104**, 269-276. https://doi.org/10.1016/j.clay.2014.12.005.

Karaman, S., Ersahin, S. and Gunal, H. (2006), "Firing temperature and firing time influence on mechanical and physical properties of clay bricks".

Keerthinarayana, S. and Srinivasan, R. (2010), "Study on strength and durability of concrete by partial replacement of fine aggregate using crushed spent fire bricks", *Buletinul Institutului Politehnic din lasi. Sectia Constructii, Arhitectura*, **56**(2), 51.

Kesegić, I., Netinger, I. and Bjegović, D. (2008), "Recycled clay brick as an aggregate for concrete", *Tehnički Vjesnik*, **15**(3), 35-40.

Kuehnen, R., Youssef, M.A. and El-Fitiany, S.F. (2022), "Influence of natural fire development on concrete compressive strength", *Fire*, **5**(2), 34. https://doi.org/10.3390/fire5020034.

Lawanwadeekul, S., Srisuwan, A., Phonphuak, N. and Chindaprasirt, P. (2023), "Enhancement of porosity and strength of clay brick fired at reduced temperature with the aid of corn cob and waste glass", *Constr. Build. Mater.*, **369**, 130547. https://doi.org/10.1016/j.conbuildmat.2023.130547.

Li, Y., Huang, L., Gao, C., Mao, Z. and Qin, M. (2023), "Workability and mechanical properties of GGBS-RFBP-FA ternary composite geopolymer concrete with recycled aggregates containing recycled fireclay brick aggregates", *Constr. Build. Mater.*, **392**, 131450. https://doi.org/10.1016/j.conbuildmat.2023.131450.

Li, Y., Huang, L., Gao, C., Qu, Y., Luo, X., Lv, B. and Chen, Z. (2024y), "Axial compressive behavior of steel reinforced GGBS-RFBP-FA ternary composite geopolymer recycled fireclay brick aggregates concrete columns", *Struct.*, **60**, 105913. https://doi.org/10.1016/j.istruc.2024.105913.

Nisha Devi, A. (2016), "Study of partial replacement by glass powder and crushed spent fire bricks in concrete", *Int. J. Eng. Res. Technol. (IJERT)*, **5**(3), 2278-0181. https://doi.org/10.1016/j.istruc.2024.105913.

Özkılıç, Y.O., Başaran, B., Aksoylu, C., Karalar, M. and Martins, C.H. (2023), "Mechanical behavior in terms of shear and bending performance of reinforced concrete beam using waste fire clay as replacement of aggregate", *Case Stud. Constr. Mater.*, **18**, e02104. https://doi.org/10.1016/j.cscm.2023.e02104.

Phonphuak, N. (2013), "Effects of additive on the physical and thermal conductivity of fired clay brick", *J. Chem. Sci. Technol.*, **2**(2), 95-99.

Phonphuak, N., Kanyakam, S. and Chindaprasirt, P. (2016), "Utilization of waste glass to enhance physical-mechanical properties of fired clay brick", *J. Clean. Prod.*, **112**, 3057-3062.

https://doi.org/10.1016/j.jclepro.2015.10.084.
Pitak, I., Baltušnikas, A., Kalpokaitė-Dičkuvienė, R., Kriukiene, R. and Denafas, G. (2022), "Experimental study effect of bottom ash and temperature of firing on the properties, microstructure and pore size distribution of clay bricks: A Lithuania point of view", *Case Stud. Constr. Mater.*, **17**, e01230. https://doi.org/10.1016/j.cscm.2022.e01230.
Poon, C.S., Lam, L., Kou, S., Wong, Y.L. and Wong, R. (2001), "Rate of pozzolanic reaction of metakaolin in high-performance cement pastes", *Cement Concrete Res.*, **31**(9), 1301-1306. https://doi.org/10.1016/S0008-8846(01)00581-6.
Ramkumar, N. and Manikandan, M. (2022), "Strength and durability of crushed fire bricks by partial replacement with fine aggregate", *J. Univ. Shanghai Sci. Technol.*, **24**(4), 28-37.
Rani, M.U. and Jenifer, J.M. (2016), "An experimental study on partial replacement of sand with crushed brick in concrete", *Int. J. Sci. Technol. Eng. (IJSTE)*, **2**(08), 316-322.
Rodsin, K. (2021), "Confinement effects of glass FRP on circular concrete columns made with crushed fired clay bricks as coarse aggregates", *Case Stud. Constr. Mater.*, **15**, e00609. https://doi.org/10.1016/j.cscm.2021.e00609.
Šebestová, P., Černý, V. and Drochytka, R. (2019), "The influence of the fireclay waste on the microstructure and the physico-mechanical properties of autoclaved aerated concrete".
Sutcu, M., Alptekin, H., Erdogmus, E., Er, Y. and Gencel, O. (2015), "Characteristics of fired clay bricks with waste marble powder addition as building materials", *Constr. Build. Mater.*, **82**, 1-8. https://doi.org/10.1016/j.conbuildmat.2015.02.055.
Tsega, E., Mosisa, A. and Fufa, F. (2017), "Effects of firing time and temperature on physical properties of fired clay bricks", *Am. J. Civil Eng.*, **5**(1), 21-26. https://doi.org/10.11648/j.ajce.20170501.14.
Vaitheki, R., Sangeetha, K., Mallika, V., Chitra, P. and Rathna, M.S.T. (2019), "Partial replacement of fine aggregate by using spent fire brick waste", *IJARIIE*, **5**, 1505-1510.
Wongsa, A., Sata, V., Nuaklong, P. and Chindaprasirt, P. (2018), "Use of crushed clay brick and pumice aggregates in lightweight geopolymer concrete", *Constr. Build. Mater.*, **188**, 1025-1034. https://doi.org/10.1016/j.conbuildmat.2018.08.176.
Zhang, M.H. and Li, H. (2011), "Pore structure and chloride permeability of concrete containing nano-particles for pavement", *Constr. Build. Mater.*, **25**(2), 608-616. https://doi.org/10.1016/j.conbuildmat.2010.07.032.

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