Scientific Reports

https://doi.org/10.1038/s41598-025-29957-5

Article in Press

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Received: 4 September 2025

Accepted: 20 November 2025

Published online: 29 November 2025

Cite this article as: Özkılıç Y.O., Karalar M., Çelik A.İ. *et al.* Microstructural, mechanical and statistical evaluation of concrete incorporating waste glass wool exposed to elevated temperatures. *Sci Rep* (2025). https://doi.org/10.1038/s41598-025-29957-5

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Microstructural, Mechanical and Statistical Evaluation of Concrete Incorporating Waste Glass Wool Exposed to Elevated Temperatures

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Abstract

The purpose of this research was to determine the effects of using waste glass wool in concrete's on the concrete's mechanical properties. Samples of concrete containing varying percentages of waste glass wool by total concrete volume (0%, 1%, 2%, 3%, 4%, and 5%) were tested after exposure to a range of temperatures: 24 °C, 400 °C, 600 °C, and 800 °C. Several tests, including compressive strength (CS), splitting tensile strength (STS), and flexural strength (FS), were then performed on the samples in the laboratory following the completion of elevated temperature. The results showed that glass wool waste material reduces the concrete CS. Conversely, experiments have shown that samples STS and FS, increase proportionally with the amount of waste glass wool. Accordingly, the concrete compressive strength decreased by 4.26%, 7.84%, 11.87%, 14.24%, and 17.27% when the mixing ratio was increased from 1% to 5%. On the other hand, by increasing the mixing ratio from 1% to 5%, concrete STS and FS were enhanced by 9.61%; 15.19%; 27.70%; 36.58%; and 60.41% and 16.91%; 29.99%; 35.73%; 45.45%; and 59.45%, respectively. FE-SEM and EDX analysis was also included. Furthermore, equations were developed to estimate the capacities of concrete, with waste glass wool, after exposure to elevated temperatures. Taguchi analysis revealed that temperature is the most critical factor affecting mechanical performance, while the addition of waste glass wool contributed to strength retention at elevated temperatures. ANOVA confirmed the statistical significance of both temperature and waste glass wool's contribution , reinforcing their combined role in producing sustainable concrete with improved high-temperature resistance. The addition of waste glass wool to concrete recycles waste glass wool and minimizes the need for new raw materials and waste disposal requirements. According to the ratio and distribution above, adding modest quantities of glass wool may lighten concrete without affecting its strength.

Keywords: Waste Glass Wool; elevated temperature; compressive strength; splitting tensile strength; flexural strength

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1. Introduction

Concrete, with its remarkable versatility, durability, and adaptability, stands as the most widely used construction material in modern infrastructure and serves as a cornerstone of global development through its extensive use in buildings, roads, bridges, and various other structures [1, 2]. As a consequence of growing environmental consciousness, the concrete industry is under pressure to reduce the use of natural resources. However, the production of traditional concrete creates serious environmental impacts largely due to the intensive use of natural resources and energy [3]. The growing need to protect natural resources, effectively manage industrial and construction waste, and reduce environmental pollution has encouraged the use of industrial and construction waste as a sustainable building material [4, 5]. Mineral wools, which include glass and glass wools, are often used as insulation materials in structures. One kind of mineral wool is called glass wool, and it has an amorphous structure, a high SiO2 content, and up to 16 weight percent of Na2O, [6, 7]. Typically, these materials are disposed of in landfills after the buildings are demolished [8]. Stone wool is a material used in the inorganic insulation process. It is also used in a broad range of industrial applications, including autos, ships, and appliances, owing to its exceptional soundproofing and sound absorption capabilities[9]. Approximately 800,000 tons of glass wool trash are produced each year in Europe [7]. This waste mostly comes from the glass wool industry and development and demolition projects. When waste glass wool is substituted for aggregate, waste glass wool can be acquired at a low cost or for free, which results in a reduction in production costs. These expenses, as well as the usage of potentially dangerous storage and disposal techniques, may be mitigated by their incorporation into concrete. Furthermore, although cement manufacture results in substantial CO_2 emissions, the use of glass wool waste as a replacement material lowers overall emissions. There are many positive aspects of incorporating waste glass wool into concrete, including its enhanced mechanical and physical characteristics, reduced environmental impact, and financial benefits. The use of this material in concrete has been the subject of several recent studies for the reasons stated above.

According to the published studies, waste glass wool has been extensively researched. An investigation was carried out by Gowri and Mary [10]. This research aimed to enhance the strength of concrete at a lower cost by including glass wool fiber, as compared with ordinary concrete. The compressive and tensile strengths of the material, were investigated by changing the proportion of fiber from 0.025% to 0.075% of the weight of the concrete. Increasing the glass wool content in concrete from 0.025% to 0.075% by total weight leads to an increase in compressive strength from 5.15% to 15.68% after 28 days. Ahmed et al.[11] performed another investigation. In this research, glass wool fiber was added to the concrete, while copper slag was used as a replacement for the fine aggregate. The study investigated the impact of different percentages of glass wool fiber (ranging from 0.2% to 0.8% of the total weight of concrete) on the strength characteristics of concrete. This was achieved by replacing 40% of the fine aggregate with copper slag. The results revealed that the inclusion of glass wool fibers at a concentration of 0.2%, led to superior performance when compared with the control concrete. Specifically, the compressive strength increased by 6%, while the split

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tensile strength increased by 6% for the first mixture and 10% for the second mixtures, respectively. However, increasing the specific percentage decreased the strength parameter. Olutoge and Oluwaseun [12] experimentally studied the influence of glass wool fiber (GWF) on the residual flexural strength (RFS) of conventionally reinforced concrete elements. Further experiments were performed on cube and cylindrical specimens to investigate the impact of the fibers on concrete including compressive and tensile strength tests. The results demonstrated a substantial 20.83% increase in the tensile strength when the fiber content was increased to 0.50%. Additionally, a 0.26% increase in compressive strength was observed when the fiber dose was increased to 0.25%. The effectiveness of self-compacting mortar under ambient conditions and at higher temperatures of 200 °C, 400 °C, 600 °C, and 800 °C was examined by Bala et al. [13] in terms of using heat-resistant paint and glass wool fiber reinforcements,. A total of sixteen mix designs were created for the use of self-compacting mortar, with 25% fly ash. These mix designs included the incorporation of glass wool fiber reinforcement at different percentages, ranging from 0% to 1.5% of the weight of cement. Additionally, the effective water-to-cement (w/c) ratio was varied throughout the mix designs, with values of 0.43, 0.49, 0.55, and 0.70. Upon concluding the investigation, it was observed that the addition of glass wool fiber and the reduction of the effective water-to-cement ratio resulted in a drop in the compressive strength of the self-compacting mortar. However, the addition of glass-wood fibers had a favorable influence on the flexural strength. Machado et al.[14] performed another investigation. In this investigation, it was determined whether the incorporation of fibers made from sugarcane bagasse and/or glass wool into concrete affected the mechanical behavior of the concrete. Characterizations of the morphology, chemistry, and physical states were performed. With the addition of only 10% glass wool to concrete, it was demonstrated that the compressive strength, flexural tensile strength, and diametrical compression tensile strength of the material increased to 34.22, 6.65, and 16.44 MPa, respectively. Olutoge [15] conducted another investigation to examine the impact of glass wool fiber on the strength characteristics of hollow concrete blocks. The mix was supplemented with glass wool fiber at varying proportions of 0%, 5%, 10%, 15%, and 20%. Subsequently, a compressive strength test was conducted. The study determined that the compressive strength of the hollow concrete block progressively increased and peaked with a 15% addition of glass-wool fiber, resulting in an overall 33% increase. Additionally, the weight of the block decreased by 1.6%. Pamu and SVSNDL [16] empirically investigated the production of clay bricks and explored the effects of using glass wool as a substitute. Bricks injected with various percentages of glass wool were examined for mechanical, physical, and durability properties. According to these tests, the bricks containing 4% glass wool exhibited the highest compressive strength and the lowest heat conductivity compared to control bricks. Jaber[17] investigated the potential integration of glass wool (fiberglass insulation) with cement mortar as a construction material for insulation. A mixture of conventional Portland cement and sand was prepared at a ratio of 1:3. Glass wool was then added to the mixture at different weight proportions ranging from 0 to 0.24 wt%. Results indicated that although adding glass wool reduced the density, heat conductivity, and compressive strength of the cement mortar, it increased its flexural strength. With the aim of improving the mechanical properties of concrete, Kim et al. [18] proposed the use of waste glass wool as an additive. In accordance with the experimental

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findings, glass wool was found to have a low level of pozzolanic activity a positive impact on both compressive and flexural strength. This experimental study determined that a volumetric addition of 0.5% in the concrete mix was optimal. To investigate the effectiveness of glass-wool residue in cement-based composites, Defáveri et al. [19] conducted a performance study. Experiments were carried out on mortars and pastes, in which 25% of Portland cement was substituted with ground glass wool residue. The results of the compressive strength tests indicated that the residue and reference mortars performed similarly, , with only a 2% decrease in compressive strength. Additionally, the use of ground glass wool residue increased the efficiency of Portland cement production, lowering the amount of natural resources used, and the level of CO2 emissions associated with clinker production. The other investigation was performed by Pamu et al.[20]. Using sand cat swarm optimization and progressive graph convolutional networks, this study introduces a unique hybrid approach to predict the mechanical characteristics of glass-wool-fiber-reinforced concrete. The main objective was to optimize the composition of glass wool fiber reinforced concrete by precisely predicting its compressive, flexural, and tensile strengths. Experiments were conducted on concrete compositions of the M20 and M30 classes, that contained glass wool fibers (0.5%–3%) and 30% ground granulated blast furnace slag replacement for this purpose. This research found that glass wool and crushed granulated blast furnace slag increase the material's strength and insulation, making it a feasible option for ecologically benign and energy-efficient construction material. Machado et al. [21] sought to assess the potential of ground glass wool waste as an additional cementitious component in cement mortar applications. To achieve this objective, cylindrical and prismatic specimens were employed to generate cement samples that replace 0.0%, 10.0%, 17.5%, and 25.0% of the cement with pulverized glass fiber. It was observed that the utilization of this supplementary cementitious material led to a decrease in the heat of hydration of the cement mortar, as well as a reduction in CO_2 emissions by approximately 15.5% in comparison to the reference experiment.

There are not many studies on the strength of glass wool in concrete. In addition to these studies, the following are available in the literature [22-40]. A survey of previous research indicates that there aren't many studies that specifically address the proportion of glass wool fibers in concrete. Moreover, hardly any research exists examining the impact of temperature. This research is motivated by this gap in the literature. Comprehensive information is provided in the following sections. This research focused on investigating the increasing use of glass wool waste during construction, specifically in relation to the amount of aggregate in the concrete mixture. To achieve this goal, a number of laboratory investigations were conducted to investigate the factors that influence the compressive, tensile, and flexural strength of concrete. Concrete samples were produced in the laboratory by adding various percentages of waste glass wool; they were then exposed to various temperatures. Six distinct groups of waste glass-wool-added test concretes with varying amounts of 0%, 1%, 2%, 3%, 4%, and 5% were designed and manufactured.

2. Experimental Program

In this investigation, glass wool waste at six different ratios was used in place of coarse aggregate across various temperatures. The studies were conducted at the laboratory of Necmettin Erbakan

University in the Department of Construction. The ideal range for employing glass wool, as studied in the literature [9, 41], is from 0% to 5% when replacing cement and from 5% to 15% when replacing aggregate. Decreases in density and strength of approximately 10% were observed in aggregate in the literature. For these reasons in this study, glass wool was added to concrete samples at proportions ranging from 1% to 5% of the volume of coarse aggregate. A total of 144 sample molds were filled with 48 cylindrical, 48 cubic, and 48 prismatic samples. Two of each set of samples were collected and placed individually in an oven at 400, 600, or 800 °C.

2.1. Materials

This research aimed to assess the impact of glass wool, a waste material commonly generated at construction sites during the installation, cutting, trimming, and replacement of insulation panels, on the environment. Large amounts of off-cuts, damaged pieces, and dismantled insulation from renovation or demolition works often end up as glass wool waste, contributing to both material losses and environmental burdens. Fig. 1 illustrates the places where the waste glass wool was collected to utilize in this study.



Fig. 1. Waste glass wool material collected from site

The maximum size of the aggregate was determined to be 16 mm. The cement used in the concrete samples was CEM I type PÇ 42.5 , which was manufactured at a Konya cement production facility. For the preparation of 1 m³ of concrete, 525 kg of cement, 262.5 kg of water, 787.5 kg of fine

aggregate, and 787.5 kg of coarse aggregate were used, corresponding to a mix proportion of 1 : 0.5 : 1.5 : 1.5 by weight. Additionally, Fig. 2 shows the waste glass wool material and its typical dimensions. The average length was taken as 8 cm.



Fig. 2. Cropped waste glass wool material and average dimensions of the utilized material

3. Test Methods

The researchers conducted a series of laboratory experiments to investigate the elements that influence the compressive and tensile strength of concrete and assess the impact. To achieve this objective, laboratory-produced concrete samples were prepared using different proportions of waste glass wool and were subjected to various temperatures. The 28-day crushing outcomes of the samples were then analyzed. In total, six distinct groups of test concrete with added waste glass wool were created. A total of 144 sample molds were filled in each of the sets, ranging from 0% to 5% waste glass wool. These molds included eight cylindrical, eight cubic, and eight prismatic samples. A total of six samples (two from each group) were individually placed in ovens set at temperatures of 400 °C, 600 °C, and 800 °C. An increase in the quantity of glass wool, which is a waste material, results in a reduction in slump value, as observed in Fig. 3. After a period of 28 days, the samples were extracted from the molds and placed in ovens set to temperatures of 400°C, 600°C, and 800°C, as shown in Fig. 4. Concrete mix ratio is given in Table 1.

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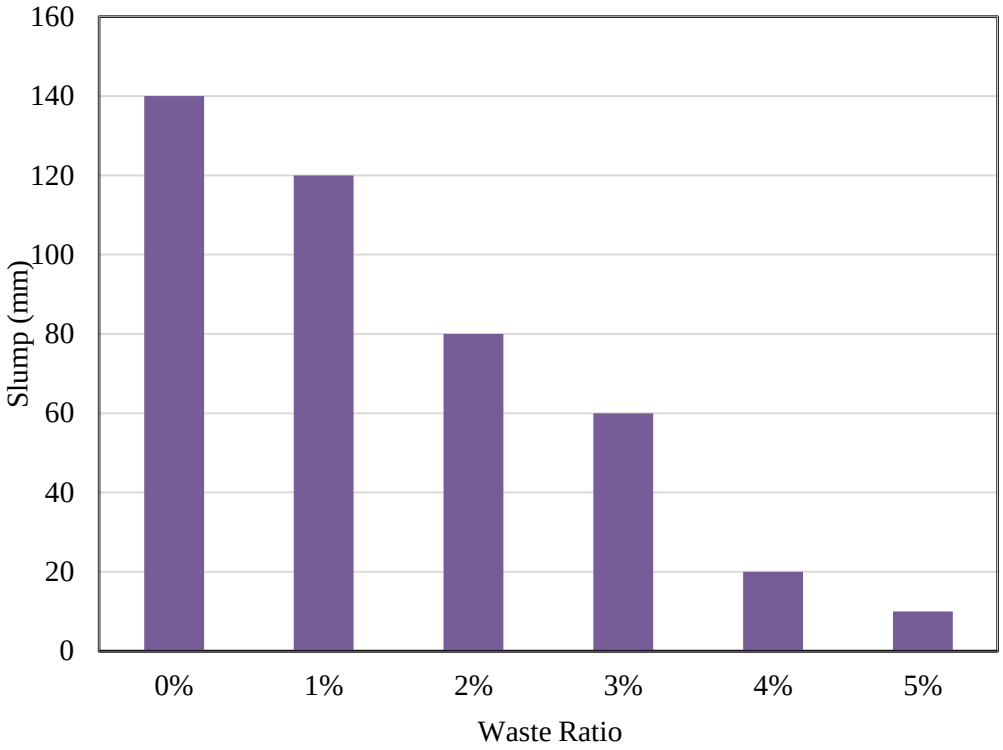


Fig. 3. Slump tests results.

Table 1. Concrete Mix Ratio (kg/m")

Sets	Mixture Percentage	Glass Wool	Cement	Water	Fine Aggregate	Coarse Aggregate
Set#1	0%	0	525	262.5	787.5	787.5
Set#2	1%	5	525	262.5	787.5	782.5
Set#3	2%	10	525	262.5	787.5	777.5
Set#4	3%	15	525	262.5	787.5	772.5
Set#5	4%	20	525	262.5	787.5	767.5
Set#6	5%	25	525	262.5	787.5	762.5





Fig. 4. Sample placement in 400°C, 600°C, and 800°C ovens and slump test

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4. Discussion and Analysis of Experimental Results

4.1. Comprehensive Evaluation of the Compressive Test Evaluation

The CS results, which are shown in Fig. 5, for the samples under test, which were made using a variety of aggregate types, such as waste glass wool . Tests were performed according to ASTM C109[42]. The greatest CS values were observed in the reference, which did not include waste glass wool, as shown in Fig. 5. Results showed that after 28 days, the reference concrete series without waste glass wool had a CS value of 27.33 MPa. The concrete strength values were determined to be 26.16, 25.18, 24.08, 23.44, and 22.61 MPa, in accordance with the selected mixing ratios. Increasing the mixing percentage from 1% to 5% resulted in a reduction in the concrete's compressive strength, ranging from 4.26% to 17.27%.

The concrete samples were subjected to temperatures ranging from 24°C to 400°C, 600°C, and 800°C. Following an increase in temperature during the oven process, the compressive strength (CS) values of the concrete samples (Set#1), were determined to be as follows: 27.33 MPa, 23.53 MPa, 19.56 MPa, and 16.89 MPa. A decrease in the CS values of 13.89%, 28.41%, and 38.18% was observed for Set #1 when the combined temperature was increased. When the percentage of waste glass wool in the mixture is raised to 1% and temperatures are varied from 24 °C, to 400 °C, 600 °C, and 800 °C, the CS values produced are as follows: 26.16, 21.57, 18.21, and 15.35 MPa. These are the results of the experiment. The CS values decreased by 17.55%, 30.38%, and 41.33% cumulatively or at different temperature increments when the temperature was raised for Set #2. When the amount of waste glass wool in the mixture was increased to 2% and the temperature was adjusted from 24 °C to 400 °C, 600 °C, and 800 °C, the CS values obtained were recorded as follows: These values are 25.18 MPa, 20.54 MPa, 17.07 MPa, and 13.13 MPa. As a result of the temperature increase in Set #3, the CS values decreased by 18.42%, 32.23%, and 47.86%. The following CS values were obtained when the quantity of waste glass wool in the mixture was raised to 3% and the temperature was varied from 24 °C to 400 °C, 600 °C, and 800 °C, respectively. 24.08 MPa, 19.77 MPa, 15.91 MPa, and 12.83 MPa were determined for the experiment. For Set #3, the CS values were reduced by 17.90%, 33.93%, and 46.74%, respectively. This result was due to the increase in temperature caused by the combination. As a result of increasing the percentage of waste glass wool in the mixture to 4% and varying the temperature from 24 °C to 400 °C, 600 °C, and 800 °C, the following CS values were obtained: 23.44, 18.54, 15.41, and 12.61 MPa. For Set #4, the CS values declined by 20.89%, 34.25%, and 46.21%, respectively. This result occurred because the temperature of the mixture rose. The primary reason for this decline is that the deterioration of the fiber-matrix interface at elevated temperatures adversely impacts performance [13]. When the amount of waste glass wool in the mixture was increased to 5% and the temperature was varied from 24°C to: 400°C, 600°C, and 800°C, the following CS values were measured. Four different readings were recorded: 22.61, 17.77, 14.55, and 12.30 MPa. For Set #5, the CS values decreased by 21.39%, 35.64%, and 45.58%, respectively.

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The increase in the combination's temperature occurred due to the situation. The behavior of the press machine of 5% of the sample at 800°C is shown in Fig. 6.

It was observed that the increase in the mixing percentage from 1% to 5% led to a decrease in the concrete compressive strength. The findings from the investigations published in the literature appear to be comparable. In practice, the packing and alignment of shorter fibers are more challenging than those of longer fibers[17, 43]. Therefore, the mixture filled with short fibers leads to an increase in the number of faults, which in turn leads to a decrease in both the density and compressive strength of the finished product [17, 43]. There was a general need for a greater quantity of water in mixes that included fibers than those without fibers [17]. The increase in the amount of glass wool causes a decrease in the hydration action of cement mixtures [17, 43, 44].

The primary reason for the reduction in the compressive strength of concrete of glass wool waste is that it is a low-density and highly porous material. Consequently, the glass wool fibers themselves are unable to contribute to load carrying, but they establish a "weak zone" in the concrete. Furthermore, glass wool often has a hydrophobic surface that makes it difficult to form a strong chemical connection with cement paste. As a result, cement hydration products (C-S-H gels) have difficulty sticking to the surface of glass fibers. Concrete's compressive strength is reduced as a consequence of the micro-voids and debonding caused by this poor adhesion at the fiber-matrix contact [17, 45]. This might be considered the detrimental impact of glass fiber addition on CS.

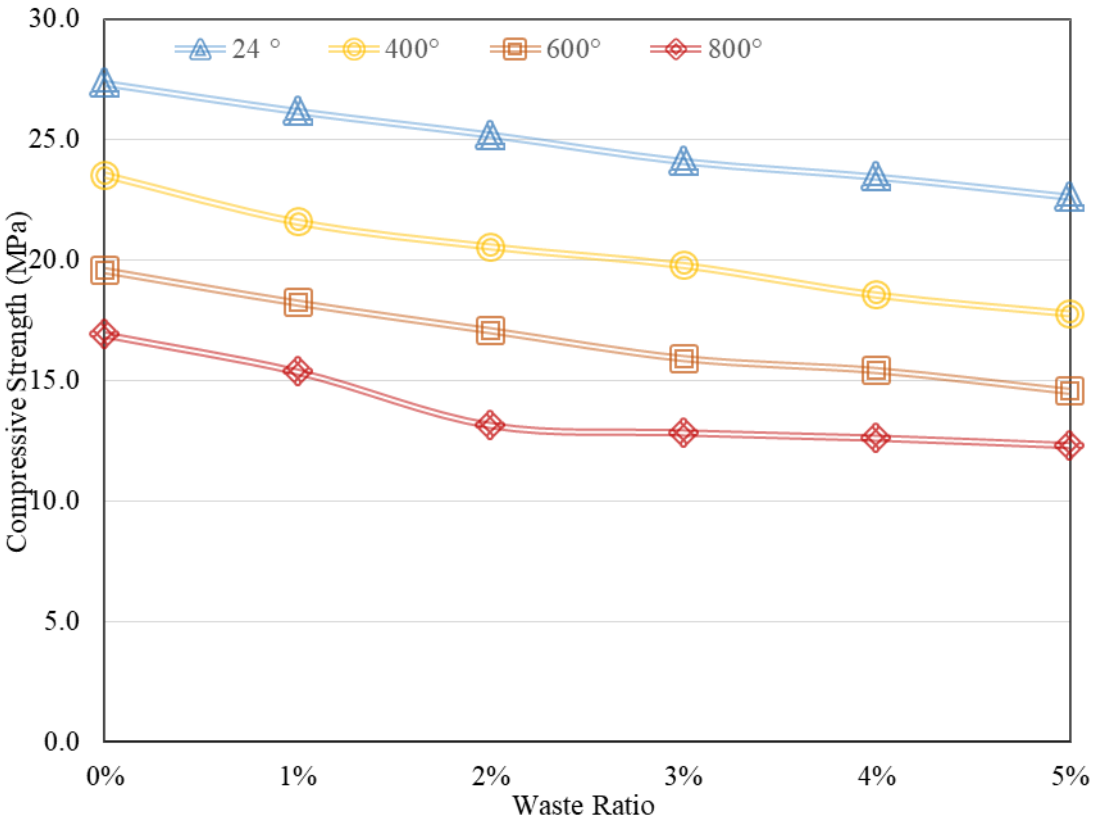


Fig. 5. Findings from the CS

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Fig. 6. Compressive behavior of 5% of the sample at 800°C.

4.2. Comprehensive Evaluation of Splitting Tensile Strength Test

According to the information shown in Fig. 6, as discussed above, the STS results do not typically follow the parallel slope as the CS results. Tests were performed according to ASTM C496[46]. As demonstrated in Fig. 7, the reference set, Set#1, that did not include any waste glass wool had the lowest STS values. After 28 days, the STS values of the reference concrete series that did not include waste glass wool were found to be 1.12 MPa. Waste glass wool was added to the concrete mixture in increments from 1% to 5%, starting at 0% and increasing up to 5%. According to the chosen mixing ratios, the STS values of the concrete were 1.12, 1.23, 1.29, 1.43, 1.53, and 1.69 MPa. As a result of raising the mixing percentage from 1% to 5%, the concrete STS improved by 9.61%, 15.19%, 27.70%, 36.58%, and 60.41%. The concrete samples were heated to temperatures of 24°C , 400°C, 600°C, and 800°C. It was established that the STS values of the concrete samples (Set#1) were as follows: 1.12 MPa, 0.95 MPa, 0.68 MPa, and 0.48 MPa. When the temperature of the combination was raised, the STS values for set #1 were observed to decrease by 15.51%, 38.88%, and 57.51%. The STS values that are obtained when the proportion of waste glass wool in the mixture is increased to 1% and temperatures are adjusted to include 24°C, 400°C, 600°C, and 800°C are: 1.23 MPa, 0.99 MPa, 0.73 MPa, and 0.52 MPa. After the temperature in the combination was elevated for Set#2, the STS results revealed decreases of 19.43%, 40.50%, and 58.03%. The STS values were obtained when the amount of waste glass wool in the mixture was increased to 3%, and the temperatures were adjusted from 24°C to 400°C, 600°C, and 800°C. The determined values were 1.29, 1.04, 0.78, and 0.62 MPa, respectively. For Set #3, the STS values decreased by 19.59%, 39.23%, and 52.22%, respectively. This result occurred because the temperature of the mixture increased. The following STS values are produced as a consequence of raising the proportion of waste glass wool in the mixture to 4% and altering the temperature to 400°C, 600°C, and 800°C: 1.43 MPa, 1.08 MPa, 0.83 MPa, and 0.65 MPa, respectively. Concerning Set #4, the STS values decreased by 24.51 %, 41.68 %, and 54.53 %, respectively. The following STS values were measured after the quantity of waste glass wool to be included in the mixture was raised to 5%, and then the temperatures were adjusted from 24°C to 400°C, 600°C, and 800°C. Fig. 8 illustrates the behavior of

the 5% sample when it was subjected to the STS test at 800 °C. A range of four measurements was noted: 1.53, 1.19, 0.88, and 0.67 MPa. With reference to Set #5, the STS values showed declines of 22.30%, 42.34%, and 56.03%, respectively. When the amount of waste glass wool to be added to the mixture is increased to 5% and the temperature is changed from 24°C to 400°C, 600°C, and 800°C, the following STS values are measured: 1.69 MPa, 1.43 MPa, 0.99 MPa, and 0.75 MPa, respectively. For Set #6, the STS results indicated drops of 15.09%, 40.98%, and 55.71%, respectively. This occurred due to the increase in the temperature of the combined components. When the mixing percentage was increased from 1% to 5%, the concrete's splitting tensile strength (STS) increased.

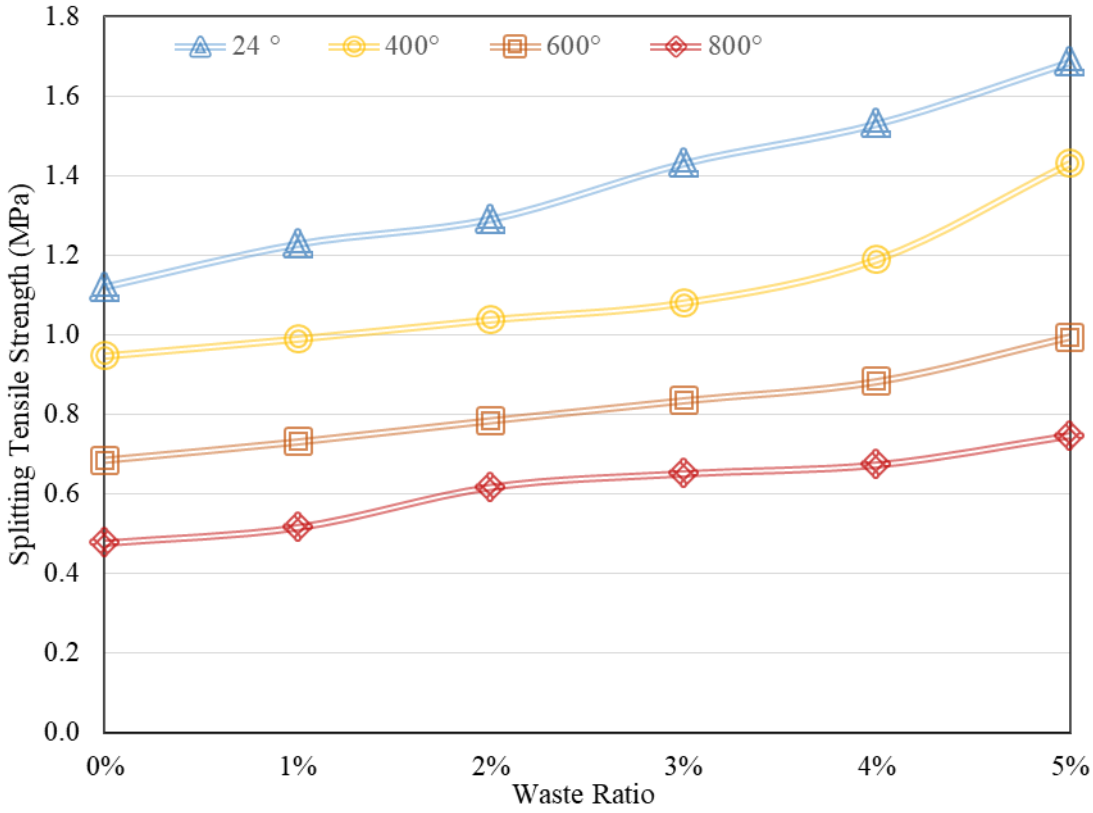


Fig. 7. Findings from the STS.

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Fig. 8. Behavior of the 5% sample in the STS test at 800°C.

4.3. Comprehensive Evaluation of the Flexural Strength Test

Fig. 9 displays the FS findings for test samples created using a range of aggregates, including waste glass wool. Set #1, called the reference set, which did not include any waste glass wool, had the lowest measured FS values, as shown in Fig. 9. Tests were performed according to ASTM C78 [47]. In accordance with the findings, the FS values of the reference concrete series, that did not contain waste glass wool, were found to be 4.36 MPa after 28 days. As was described before, waste glass wool was added to the concrete mixture in the following increments: from 1% to 5%. As a result of the mixing ratios that were selected, the specific FS values of the concrete were 5.09, 5.66, 5.91, and 6.34 MPa and 6.95 MPa. Raising the mixing proportion from 1% to 5% improved the concrete's FS to 16.91%, 29.99%, 35.73%, 45.45%, and 59.45%. Temperature ranges of 24°C–400°C and temperature points of 600°C, and 800°C were applied to the concrete samples. As a result of this investigation, the FS values of the concrete samples (Set#1) were 4.36 MPa, 3.70 MPa, 2.82 MPa, and 2.51 MPa. The FS values for set #1 were found to decrease by 15.07%, 35.35%, and 42.31% respectively when the combination temperature was increased. When the percentage of waste glass wool in the mixture was raised to 1% and the temperature was varied from 24 °C to 800 °C, in increments of 400 °C and 200 °C, the FS values were 5.09, 4.37, 3.41, and 2.87 MPa, respectively. Following an increase in the

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temperature of the combination for Set #2, FS findings showed decreases of 14.14%, 33.12%, and 43.65%, respectively. When the quantity of waste glass wool in the mixture was raised to 2% and the temperature was varied from 24 °C to 400 °C, then to 600 °C, and finally to 800 °C, each of the FS values at these temperatures was noted. The obtained values were 5.66, 5.01, 4.18, and 3.46 MPa, respectively. Furthermore, regarding Set#3, the FS values decreased by 11.60%, 26.25%, and 38.85%. Because the quantities of waste glass wool in the mixture were increased to 3% and the temperatures were changed from 24 °C to 400 °C, 600 °C, and 800 °C, the following FS values were generated. The values that were identified are as follows: 5.91 MPa, 5.27 MPa, 4.60 MPa, and 3.82 MPa. For Set #4, the FS values declined by 10.82%, 22.21%, and 35.46%, respectively. By increasing the amount of waste glass wool included in the mixture to 4% and adjusting the temperature from 24 °C to 400 °C, 600 °C, 800 °C, the following FS values are measured: 6.34 MPa, 5.53 MPa, 4.74 MPa, and 4.12 MPa. With regard to Set #5, with values of 6.95 MPa, 5.98 MPa, 4.99 MPa, and 4.41 MPa, the FS values decreased by 12.73%, 25.25%, and 34.98%, respectively. Increasing the quantity of waste glass wool incorporated into the mixture to 5% and altering the temperature resulted in the following FS values being measured: 6.95, 5.98, 4.99, and 4.41 MPa. For Set #6, the FS values revealed drops of 13.96%, 28.12%, and 36.47%. The FS test behavior for the 5% sample at 800°C is shown in Fig.10.

Raising the proportion of the mixture from 1% to 5% resulted in an increase in the FS of the concrete. The impact of temperature is contrary to expectations with respect to the FS strength of concrete. When the weight percentage of glass wool increased, the flexural strength increased slightly, as shown in Fig. 9. Similar findings were observed in previous research [17]. One possible explanation for this behavior is that the specimens tested in the flexural test are exposed to tension more than compression [17]. As a result, the fibers of glass wool can withstand tensile strength greater than that of the cement mortar matrix, which, in turn, leads to an increase in effective crack energy [10, 17]. The addition of glass wool to the cement mortar increased plastic deformation, partially absorbed energy, and lengthened the fracture propagation route[17]. Consequently, the increase in the percentage of glass wool in the cement mortar improved both the fracture energy and the flexural strength.

Glass wool fibers function as microfibers that are dispersed within the matrix phase of concrete, bridging fracture surfaces as the concrete begins to crack under load. In this way, the concrete may absorb energy and undergo greater deformation before breaking by delaying or rerouting the spread of cracks. This leads to enhanced ductility and load-bearing capability, thus augmenting flexural strength. Furthermore, the mechanical development of microcracks within the concrete is inhibited by glass wool fibers, which distribute stresses at the crack ends. This is especially useful for tensile regions subjected to flexural stresses, enhancing the FS value [9, 25]. This can be called the positive effect of glass fiber addition on FS.

The relationship between compressive strength and flexural strength is given in Fig. 11. The compressive strength clearly decreases, as the sample's flexural strength rises. The main reason for this is that glass wool waste reduces the compressive strength of concrete due to its low density and highly porous material, On the other hand, in FS behavior, glass wool fibers function as microfibers

dispersed within the concrete's matrix phase, bridging fracture surfaces when the concrete begins to crack under load. This allows concrete to absorb energy and undergo greater deformation before fracture by delaying and/or redirecting crack propagation. This, in turn, increases ductility and load-carrying capacity, thereby increasing flexural strength.

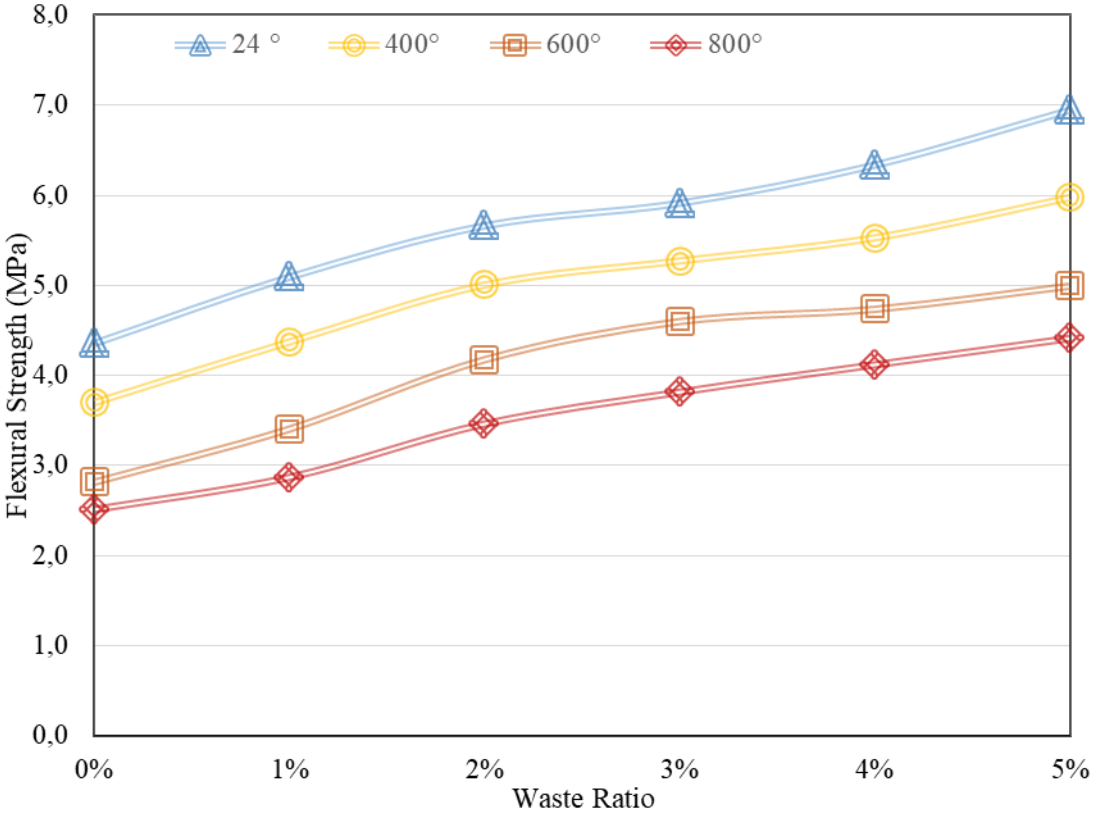


Fig. 9. Findings from the FS

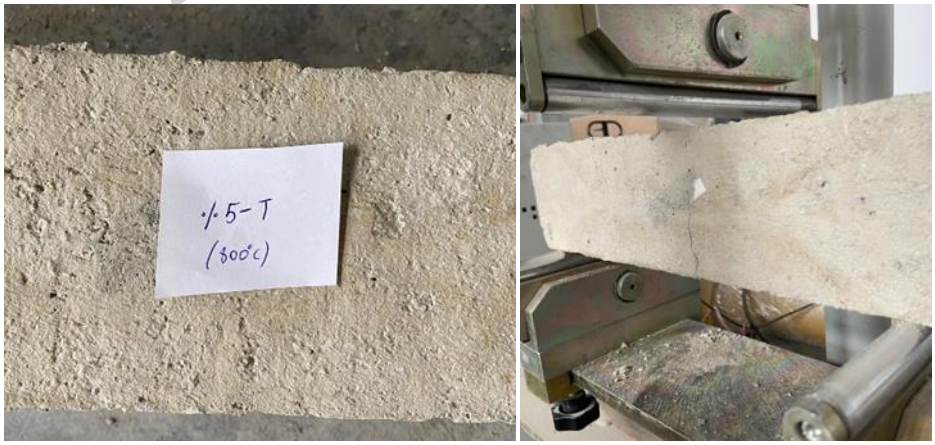


Fig. 10. FS test behavior for the 5% sample at 800°C.

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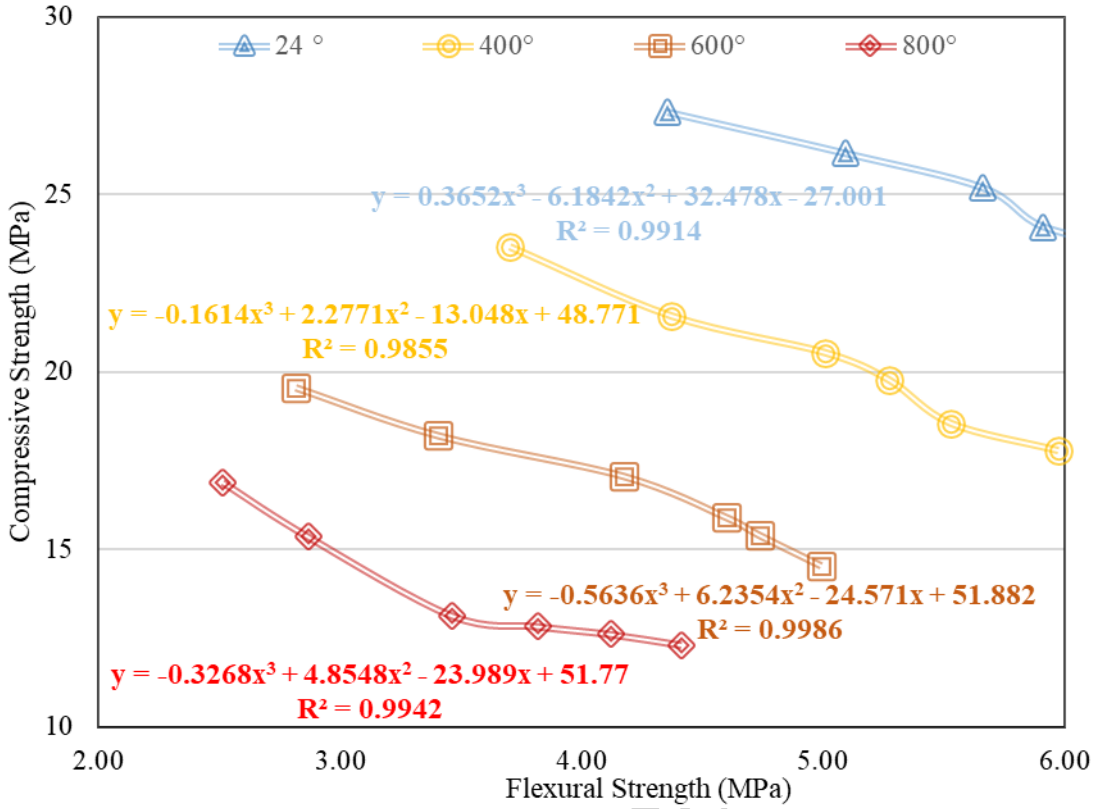


Fig. 11. Correlation between CS with the FS

5. FE-SEM analysis

Field Emission Scanning Electron Microscopy (FE-SEM) analysis results hold critical importance in determining the morphological characteristics of materials [48]. These analyses provide a detailed examination of the sample's surface structure, particle size, and distribution, thereby revealing the material's microstructural properties. In this way, they offer valuable insights into the material's durability, bonding capacity, and overall performance. The FE-SEM images in Fig. 12 reveal that the addition of glass wool creates various effects on the concrete matrix structure. It can be observed that the glass wool fibers are well distributed within the concrete and achieve good bonding. Glass wool fibers appearing in irregular clusters suggest that ensuring fiber homogeneity within the concrete matrix may not be challenging [49]. Additionally, microstructures concentrated around the fibers may contribute to enhancing the material's mechanical strength. However, pores and irregular particles could form weak points affecting concrete strength. This analysis may be useful for understanding the potential effects of waste glass wool additives on the mechanical properties of concrete. In the image shown in Fig. 12 (a), the glass wool fibers appear to be oriented longitudinally and arranged in a specific order. The parallel alignment of the fibers indicates that they are likely distributed evenly within the material, contributing to crack control. While the fiber distribution within the structure reduces compressive strength, it appears to increase flexural strength. In Fig. 12 (b), the image obtained at moderate magnification allows for a more detailed examination of the matrix surrounding the fibers. Fine particles or microstructures are observed around the fibers, and a dense bonding is noted, which may enhance the material's durability. In Fig. 12c, the image at a higher magnification

provides a detailed view of the surface structure of particles within the matrix. Irregular particles and pores are observed in the microstructure of the concrete. This irregularity may reflect the non-uniform structure of the concrete matrix or the voids formed during the hydration process. Such voids or irregularities could negatively impact the mechanical strength of the concrete and reduce its durability. Fig. 12 (d) shows an image captured at the highest magnification, revealing much finer structures within the matrix and structural details at the nanometer scale. In this image, gel-like structures, hydration products, and very fine, branched structures are observed. Such structures indicate the presence of binding hydration products such as calcium silicate hydrate (C-S-H). Glass wool fibers interact with aggregates and the binder, increasing strength [50]. These products could contribute to the durability of the concrete forming a binding layer between the glass wool fibers and the matrix.

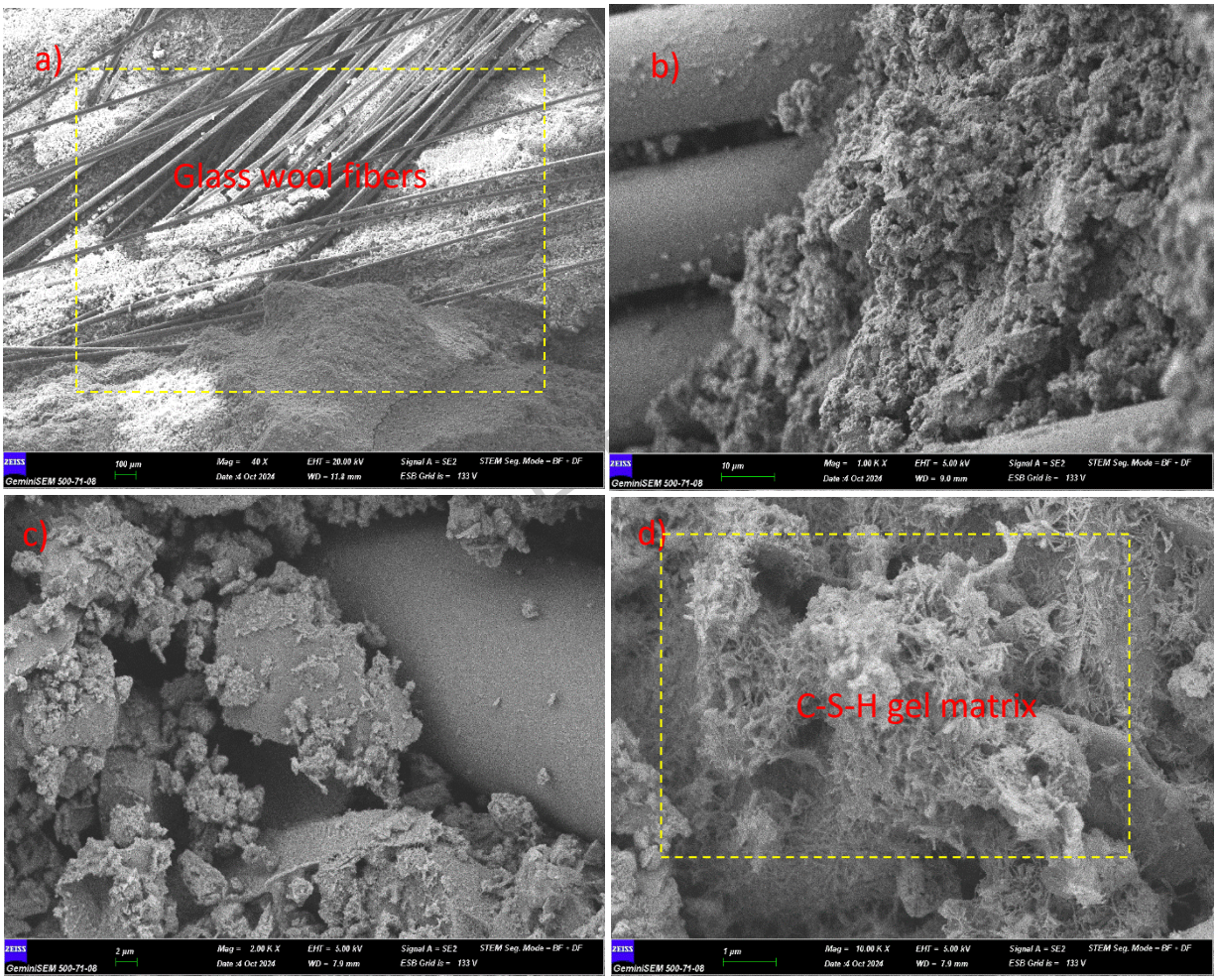


Fig. 12 FE-SEM analysis results

6. EDX Analysis

The Energy Dispersive X-ray Spectroscopy (EDX) method identifies the elements that constitute a substance by measuring the energy distribution generated from the X-ray emissions of the material [51]. The analysis of the samples was conducted using EDX in conjunction with FE-SEM. According

to the analysis results in Fig. 13, oxygen (O) is the most abundant element, with a weight percentage of 50.86% and an atomic percentage of 69.58%. This high oxygen content indicates the presence of oxide compounds in the sample, particularly silicates and calcium oxide. Calcium (Ca) is the second most common element, with a weight percentage of 29.8% and an atomic percentage of 16.28%. This significant amount of calcium suggests that the sample contains calcium-based compounds, especially calcium-containing phases such as C–S–H, which are common in cementitious structures. Silicon (Si), with a weight percentage of 11.12% and an atomic percentage of 8.67%, indicates the presence of compounds such as SiO_2, which are essential for concrete. The presence of Aluminum (Al) at a moderate level, with a weight percentage of 3.81%, indicates aluminosilicate structures. This finding also points to the inclusion of aluminum oxide (Al_2O_3) in the sample's chemical composition. Potassium (K) is present at a concentration of 1.07%, indicating a low concentration. Iron (Fe), with a weight percentage of 2.41% and an atomic percentage of 0.95%, signifies a small amount of iron in the sample. Iron can be present as an additive in building materials, contributing to strength properties. Magnesium (Mg) is found in trace amounts at a weight percentage of 0.93%.

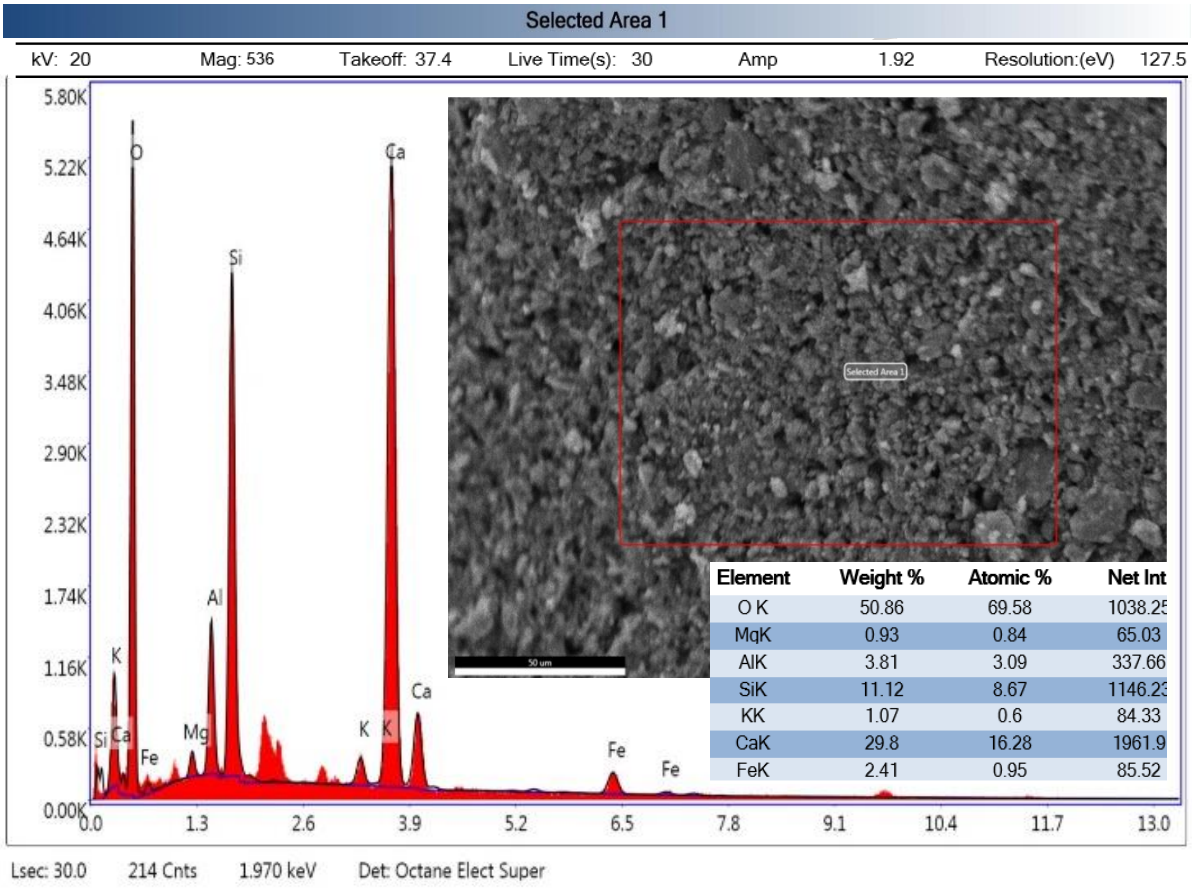


Fig. 13. EDX analysis result-1. area

Fig. 14 presents the EDX data obtained from another region of the concrete sample produced with the addition of glass wool, showing the primary elements it contains and their respective ratios. Oxygen (O) is found at the highest concentration, with a weight percentage of 52.3% and an atomic percentage of 70.42%. This high oxygen content very close to the value in Fig. 13 indicates a

homogeneous distribution throughout the structure. Calcium (Ca) is the second most abundant element, with a weight percentage of 27.63% and an atomic percentage of 14.85%. Similar to the previous image, this suggests the formation of calcium silicate hydrate (C–S–H) phases. Silicon (Si), with a weight percentage of 12.57% and an atomic percentage of 9.64%, is present in an amount comparable to that in the previous region. The presence of silicate compounds like SiO_2 contributes to the structural integrity of the concrete. Aluminum (Al), at a weight percentage of 3.82%, indicates the presence of aluminum-containing compounds, such as aluminosilicate structures. These structures may reinforce the microstructure of the concrete, a process enhanced by the addition of glass wool. Potassium (K) is found in a weight percentage of 1.13%, indicating a low concentration within the concrete. Iron (Fe), with a weight percentage of 1.7% and an atomic percentage of 0.66%, is present in a small amount and may contribute to the material's strength properties. Magnesium (Mg), at a weight percentage of 0.87%, is also found in low concentration and potentially plays a minor role in enhancing the durability of the concrete. In conclusion, the concrete sample produced with glass wool has notably high proportions of calcium, oxygen, and silicon, which play a significant role in enhancing the structure's durability and strength. These components strengthen the bonding of the glass wool additive within the concrete matrix, positively impacting the sample's overall performance.

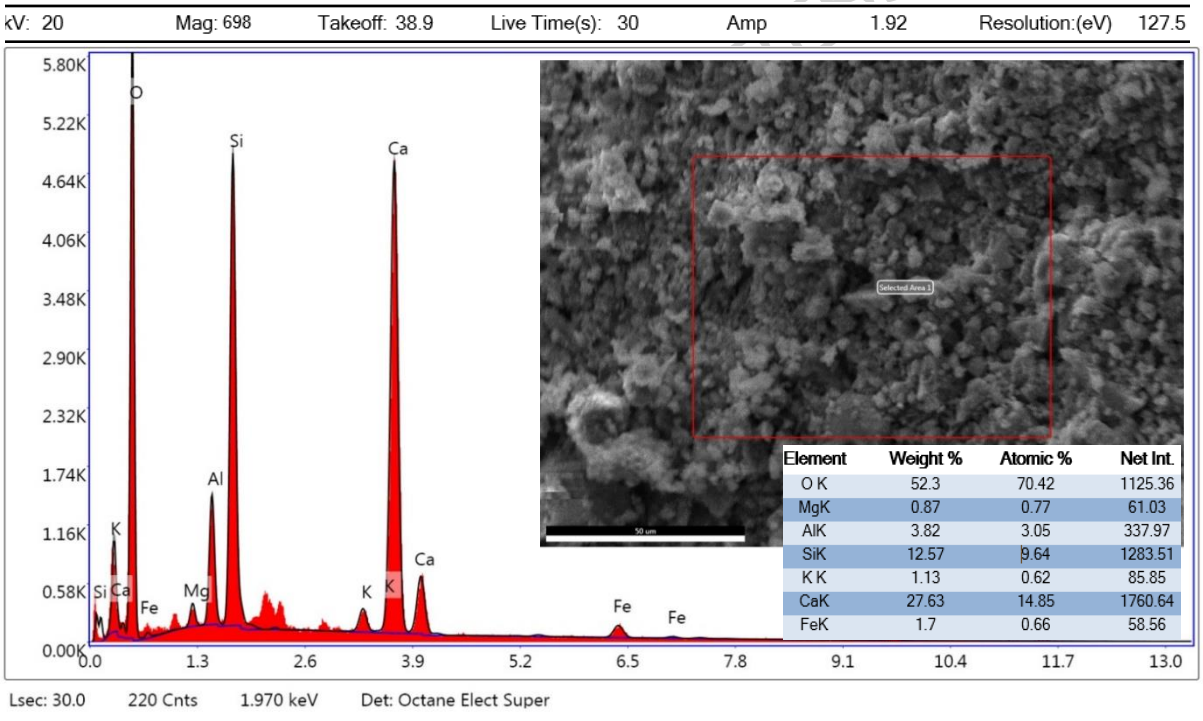


Fig. 14. EDX analysis result-2. Area

The spectra of both regions shown in Figures 13 and 14 exhibit similar characteristic peaks corresponding to the main elements O, Si, Al, and Ca, which are typical components of the pozzolanic matrix. The quantitative results reveal a close agreement between the two analyzed areas: while oxygen and silicon dominance is maintained, calcium and aluminum contents are consistent within a narrow range (O≈51–53 wt%, Ca≈27–30 wt%, Si≈11–13 wt%, Al≈3.8 wt%). These minor differences

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are within the expected experimental tolerance and confirm that the elemental composition is uniformly distributed across the sample surface. Therefore, the comparison of multiple EDX points shows a high degree of repeatability and demonstrates that the mixture exhibits good chemical homogeneity without local enrichment or depletion of the main elements.

7. Statically Analysis

7.1. Taguchi analysis

The Taguchi analysis results presented in the graph in Fig. 15 reveal the effects of varying waste glass wool (WGW) replacement at different temperatures (24 ℃, 400 °C, 600 °C, and 800 °C) on the mechanical performance of concrete. Signal-to-Noise Ratio (S/N) is a criterion that considers the desired (useful) variability in experimental results as "signal" and the undesirable (random, uncontrollable) variability as "noise." The Taguchi method aims to make the system more stable and robust by reducing the effects of "noise" in the process. The evaluation of SN ratios (“larger is better”) shows which parameters are more advantageous in terms of concrete strength. According to the results, SN ratios decrease in all series as the temperature increases. This indicates that high temperatures negatively affect the mechanical properties of concrete and that strength loss reaches its most pronounced level at 800 °C. On the other hand, increasing the WGW substitution provided a partial improvement in strength. Specifically, a 5% WGW addition showed the highest SN ratios at all temperature levels and yielded optimal results in terms of strength. This effect can be explained by WGW acting as a micro-reinforcement, limiting crack propagation and partially preserving structural integrity under high temperatures. Furthermore, while the effect of WGW addition is limited at low temperatures (24 °C), the difference becomes more pronounced with a 3–5% WGW addition at high temperatures. This indicates that WGW contributes particularly to high-temperature resistance.

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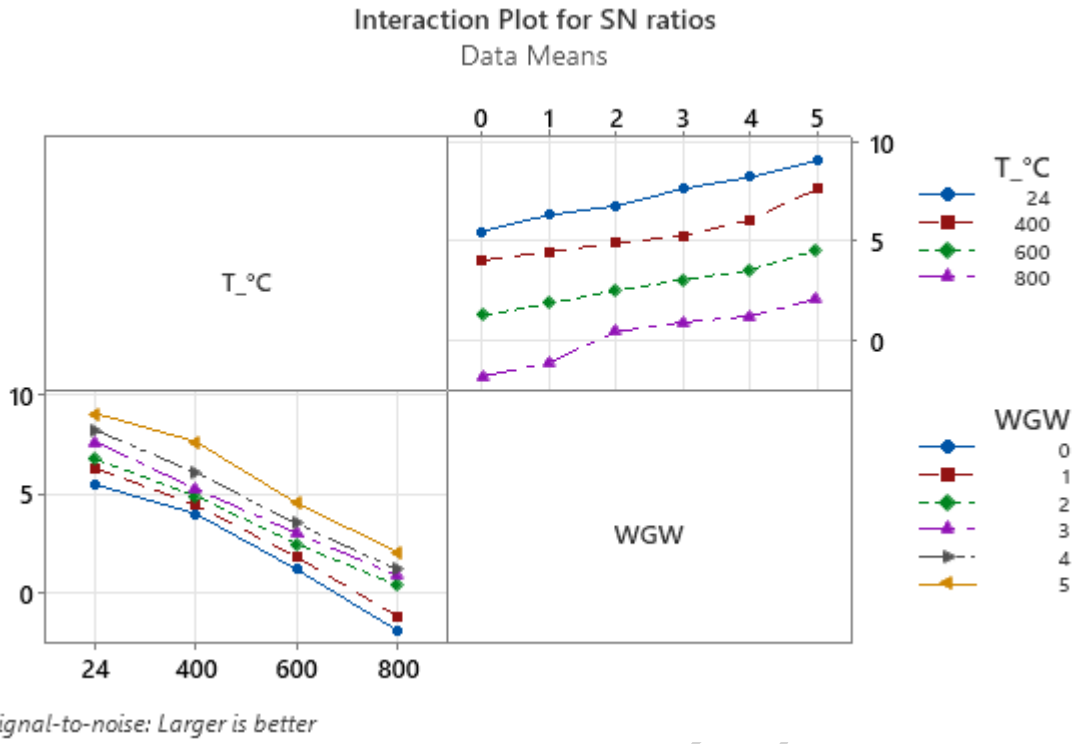


Fig 15. Taguchi Analysis: FS; CS; STS versus T_°C; WGW

6.2 Analysis of Variance (ANOVA)

According to the ANOVA results in Table 2, temperature (T_°C) and waste glass wool (WGW) have statistically significant ($p < 0.05$) effects on the FS, CS, and TST strengths of concrete. The temperature factor, in particular, stands out as the most dominant with a very high F-value (191.14) and a very low p-value (<0.0001). WGW substitution also has a significant effect, contributing to strength ($F = 24.44$; $p < 0.0001$). The model's coefficient of determination in Table 3 ($R^2 = 97.89\%$; adjusted $R^2 = 96.76\%$; estimated $R^2 = 94.60\%$) is quite high and indicates that the model strongly explains the data..

Table 2. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
T_°C	3	2,03357	0,677857	191,14	0,0000000000036
WGW	5	0,43329	0,086659	24,44	0,0000010326525
Error	15	0,05320	0,003546		
Total	23	2,52006			

Table 3. Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0595522	97,89%	96,76%	94,60%

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The linear distribution of residuals in the normal probability plot in Fig. 16, confirms that the model assumptions are valid and the analysis results are reliable. These findings confirm that temperature is the primary determinant of strength loss, but WGW contribution at appropriate ratios reduces these losses and improves concrete performance.

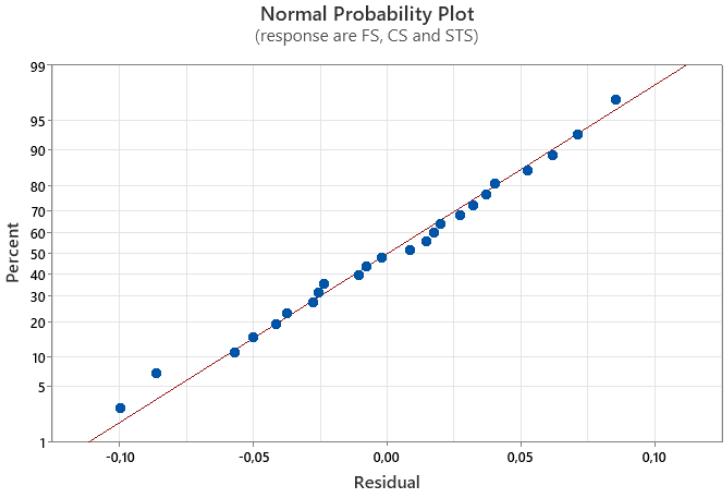


Fig. 16. The normal probability plot

8. Prediction of Capacity

The use of waste glass wool had a negative impact on compressive strength, while exerting a positive effect on splitting tensile strength and flexural strength. This is reflected in the predicted equations. Three different equations were created to predict the capacities of concrete containing waste glass wool. The effects of elevated temperatures were also included in these equations.

The compressive strength, splitting tensile strength, and flexural strength of concrete with waste glass wool exposed to elevated temperatures can be calculated using Equations 1, 2, and 3, respectively.

$f_c = \left[f_{c0} \times (1-5\alpha) \right] \times \left[1-(T-24) \times 0.0006 \right]^{0.8}$	(1)
$f_t = \left[f_{t0} \times (1+10\alpha) \right] \times \left[1-(T-24) \times 0.0008 \right]^{0.8}$	(2)
$f_f = \left[f_{f0} \times (1+12\alpha) \right] \times \left[1-(T-24) \times 0.0006 \right]^{0.8}$	(3)

where fc0, ft0, and ff0 are the compressive strength, splitting tensile strength, and flexural strength of reference concrete, respectively. T is the elevated temperature and α is the ratio of waste glass wool. Figs 17, 18, and 19 depict the comparison between the actual and predicted strengths for the concrete with waste glass wool.

The average ratio of predicted compressive strength to actual compressive strength is 1.006. The maximum, minimum, and standard deviation of this ratio are 1.103, 0.881, and 0.048. The average ratio of predicted splitting tensile strength to actual splitting tensile strength is 0.989. The maximum, minimum, and standard deviation of this ratio are 1.134, 0.909, and 0.055. Finally, the average ratio

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of predicted splitting tensile strength to actual splitting tensile strength is 1.032. The maximum, minimum, and standard deviation of this ratio are 1.136, 0.907, and 0.052. These results indicate that the predicted equations can accurately estimate the capacity of the concrete with waste glass wool, following exposure to elevated temperatures.

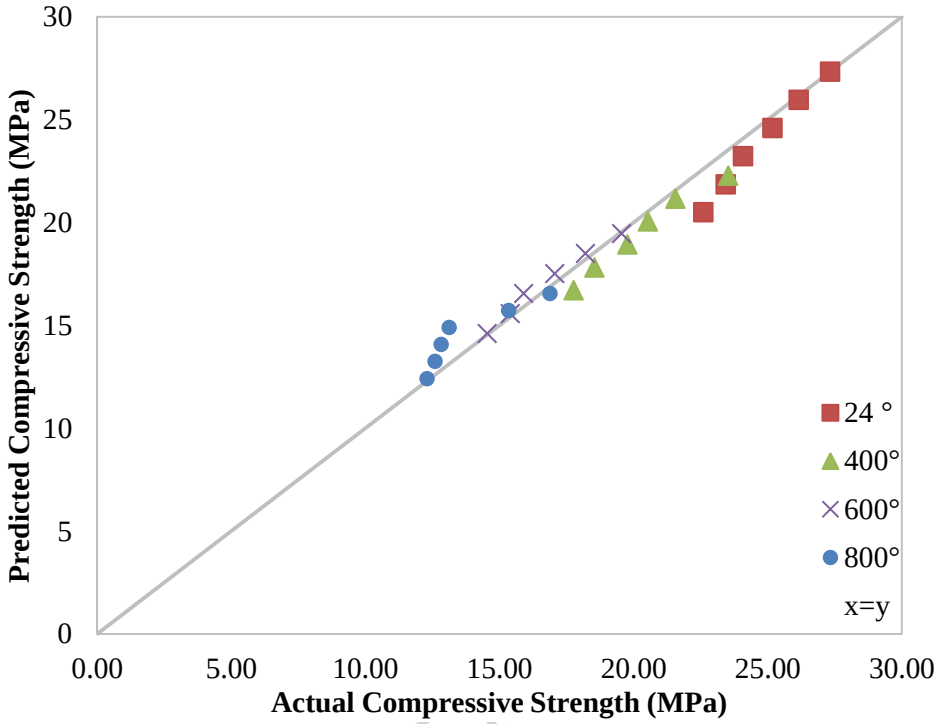


Fig. 17. Comparison of actual compressive strength to predicted compressive strength

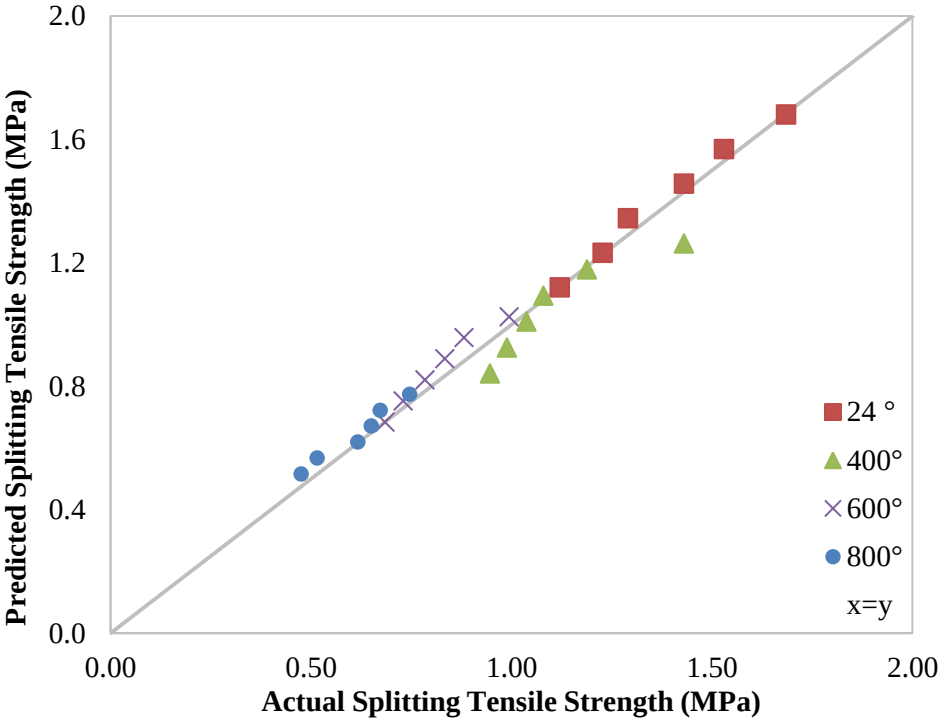


Fig. 18. Comparison of actual splitting tensile strength to predicted splitting tensile strength

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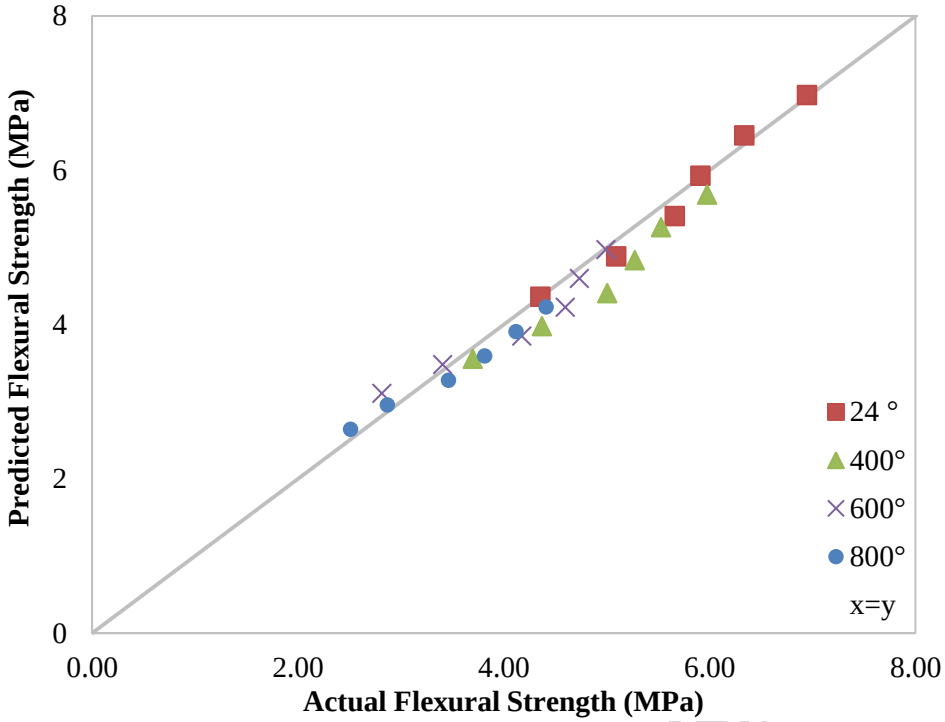


Fig. 19. Comparison of actual flexural strength to predicted flexural strength

9. Conclusion

The primary objective of this research was to examine the extent to which the use of glass wool waste during construction is related to the quantity of aggregate used in the concrete mixture. Concrete samples were manufactured in a controlled environment by adding different percentages of glass wool waste to the mix and then subjecting the samples to different temperatures. Different proportions of waste glass wool from 1% to 5% relative to the volume of coarse aggregate were used to make concrete samples. Additionally, samples were separated and placed in the furnaces to 400°C, 600°C, and 800°C. As a result of the experimental studies, the following findings emerged.

- The workability of freshly mixed concrete decreased significantly as the quantity of glass wool increased. This reduction was observed in new concrete combinations of 4% and 5%.
- Glass wool waste material reduces the CS of concrete in cubic samples when the concrete is not oven-cured. Furthermore, when placed in an oven, it was observed to diminish the strength of the concrete. Increasing the mixing ratio from 1% to 5% reduced the concrete compressive strength by 4.26%, 7.84%, 11.87%, 14.24%, and 17.27% at different points.
- Observations have shown that the STS of cylindrical samples increases in direct proportion to the quantity of the glass wool material and the temperature of the oven under consideration. By increasing the mixing ratio from 1% to 5%, concrete's splitting tensile strength (STS) STS increased by 9.61%, 15.19%, 27.70%, 36.58%, and 60.41%.

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- Adding waste glass wool improved the flexural capacity. Raising the cement mixing ratio from 1% to 5% improved concrete's flexural strength by 16.91%, 29.99%, 35.73%, 45.45%, and 59.45%.
- Although waste glass wool is not affected by elevated temperatures up to 800°C, concrete is affected by these temperatures, therefore, strength degradation was observed . The flexural strength capacity was least affected by the elevated temperature.
- Taguchi analysis results indicate that temperature is the most critical parameter for concrete's mechanical performance, but appropriate amounts of WGW can limit strength losses at elevated temperatures. This suggests that WGW can be an effective admixture in the production of sustainable, high-performance concrete.
- In the FE-SEM images, extremely fine structures and nanoscale structural details within the matrix are visible. Gel-like hydration products and very thin, branched structures are observed, indicating the presence of compounds such as C-S-H. These formations contribute to the durability of the concrete and may act as a binding layer between the glass wool fibers and the matrix. According to the EDX analysis, this concrete sample produced with glass wool shows high levels of calcium, oxygen, and silicon. These elements play a critical role in enhancing the structure’s durability and strength.
- ANOVA results showed that both temperature and WGW admixture had a statistically significant effect on the mechanical properties of concrete ($p<0.05$). Temperature, in particular, stood out as the most dominant factor, while WGW admixture played a role in reducing strength losses at elevated temperatures. This finding supports the results obtained with the ANOVA Taguchi analysis.
- The proposed equations can accurately predict the mechanical capacities.
- The standardization of glass wool waste is a challenging task due to significant variability in the chemical composition, fiber size, and bonded resin residual from one production to another. Additionally, enough information must be supplied for every aspect of waste glass wool performance in concrete, including adhesion, strength, crack management, long-term behavior, cost, etc. Comprehensive and consensus-based data is not yet available, although the literature currently contains limited data. Consequently, more investigation is necessary.

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Funding: The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this work through Large Research Project under grant number RGP2/601/45.

Acknowledgements: The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this work through Large Research Project under grant number RGP2/601/45.

Data Availability: All data generated or analyzed during this study are included in this published article

Competing Interest: The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome

Author Contributions Statement: Conceptualization, M.K., Y.O.Ö.; methodology, M.K., Y.O.Ö.; formal analysis, M.K.; investigation, Y.O.Ö; data curation, M.R.A., A.İ.Ç., M.A.M.; writing—original draft preparation, M.K., M.R.A., A.İ.Ç. M.A.M.; writing—review and editing, M.K., M.R.A., A.İ.Ç., Y.O.Ö. M.A.M.; visualization, M.R.A., A.İ.Ç. M.A.M.; Funding, E.A. All authors have read and agreed to the published version of the manuscript.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order improve several important aspects of writing, such as readability, grammar, spelling, and tone of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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References

[1] Mohanta NR, Murmu M. A Review on the Utilization of Steel Slag as Alternative Coarse Aggregate in Concrete: Transforming Waste into Wealth. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2025.

[2] Mohanta NR, Murmu M. Exploring the combined impact of coarse linz-donawitz slag and basalt fiber on the properties of concrete. Journal of Building Pathology and Rehabilitation. 2024;10:20.

[3] Mohanta NR, Murmu M. Comparative study on the effect of incorporation of Linz-Donawitz slag as coarse aggregate in concrete reinforced with different fibers. Innovative Infrastructure Solutions. 2024;9:76.

[4] Batayneh M, Marie I, Asi I. Use of selected waste materials in concrete mixes. Waste management. 2007;27:1870-6.

[5] Mohanta NR, Murmu M. Evaluating The Co-Relationship Between the Mechanical Properties of Steel Slag Aggregate Concrete Reinforced with Steel Fiber. Engineering Research Express. 2025.

[6] Adediran A, Lemougna PN, Yliniemi J, Tanskanen P, Kinnunen P, Roning J et al. Recycling glass wool as a fluxing agent in the production of clay-and waste-based ceramics. Journal of Cleaner Production. 2021;289:125673.

[7] Lemougna PN, Yliniemi J, Nguyen H, Adesanya E, Tanskanen P, Kinnunen P et al. Utilisation of glass wool waste and mine tailings in high performance building ceramics. Journal of Building Engineering. 2020;31:101383.

ARTICLE IN PRESS

[8] Yliniemi J, Kinnunen P, Karinkanta P, Illikainen M. Utilization of mineral wools as alkali-activated material precursor. Materials. 2016;9:312.
[9] Lim C-S, Jang D-S, Kim J-C, Kim H-S, Lee J-J. A Study on the Applicability of Waste Glass Wool and Waste Mineral Wool as Fiber Reinforcement. Applied Sciences. 2023;13:10738.
[10] Gowri R, Mary MA. Effect of glass wool fibres on mechanical properties of concrete. International journal of engineering trends and technology. 2013;4:3045-8.
[11] Ahmed EA, Khan EMK, Ahmad SA, Hussain A. Studying the Properties of Concrete with Copper Slag and Glass Wool Fibre. Int J Emerg Trends Eng Res(IJETER). 2016;4:226-31.
[12] Olutoge F, Oluwaseun O. Residual strength and post-cracking behaviour of glass wool fibre-reinforced concrete embedded with steel reinforcement.
[13] Bala A, Gupta, S., & Matsagar, V. (2023). Influence of glass wool fiber reinforcement and heat resistant coating on behavior of self-compacting mortar at elevated temperatures. Construction and Building Materials, 392, 131876.
[14] Preve Machado J, da Silva T, Henrique Borgert C, Rosso Neto L, Batista Gesuino D, de Oliveira J et al. Mechanical behavior of cementitious composites reinforced with the fiber of sugarcane bagasse and glass wool waste. International Journal of Environmental Science and Technology. 2023;20:3765-74.
[15] Olutoge F. Effects of Glass Wool Fibre on the Strength Properties of Hollow Sandcrete Block. British Journal of Applied Science & Technology. 2017;21:1-9.
[16] Pamu Y, SVSNDL P. An experimental analysis for clay bricks manufacturing with partial replacement of glass wool. Australian Journal of Structural Engineering. 2023;24:294-309.
[17] Jaber HA. Effect of glass wool addition on some properties of cement mortar. Eng & Tech Journal. 2016;34.
[18] Kim J-T, Choi W-H, Chung C-W, Lee J-Y. Effect of Waste Glass Wool on Mechanical Properties of Concrete. Journal of the Korea Institute of Building Construction. 2016;16:117-23.
[19] Defáveri K, Mendes J, de Carvalho JF, Fontes W, Peixoto R, Brigolini G. Glass wool residue: a potential supplementary cementitious material. ACI Materials journal. 2019;116:43-9.
[20] Pamu Y, Kona M, Samarthi P, Pamu VS. Enhancing Concrete's Structural Integrity: A Novel Approach for Predicting the Mechanical Properties of Glass Wool Fiber Reinforced Concrete. The Structural Design of Tall and Special Buildings. 2025;34:e70035.
[21] Machado J, Gesuino D, Meurer K, Wanderlind M, Pereira F, Junca E. Production of supplementary cementitious materials using glass wool residues. International Journal of Environmental Science and Technology. 2025;22:2161-76.
[22] Lemougna PN, Yliniemi J, Adediran A, Luukkonen T, Tanskanen P, Finnilä M et al. Synthesis and characterization of porous ceramics from spodumene tailings and waste glass wool. Ceramics International. 2021;47:33286-97.
[23] Lemougna PN, Adediran A, Yliniemi J, Luukkonen T, Illikainen M. Effect of organic resin in glass wool waste and curing temperature on the synthesis and properties of alkali-activated pastes. Materials & Design. 2021;212:110287.
[24] Sharma P, Bhanot VK, Singh D, Undal H, Sharma M. Research work on fiber glass wool reinforced and epoxy matrix composite material. Int J of Mech Eng & Robotics Res. 2013;2:106-24.

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ARTICLE IN PRESS

[25] Defáveri K, Fernandes Cotta J, Pereira da Fonseca Elói F, Franco de Carvalho JM, Fiorotti Peixoto RA, Brigolini Silva GJ. Effects of Glass Wool Residue Recycled Admixtures on the Properties of Portland Cement-Based Composites. Journal of Materials in Civil Engineering. 2022;34:04022301.
[26] Abass RU. Re-Use of Glass Wool Fiber as New Composite Polyester System. Engineering and Technology Journal. 2018;36.
[27] Goode AH, Tyrrell ME, Feld IL. Glass wool from waste glass: US Department of Interior, Bureau of Mines; 1972.
[28] Alsalman A, Assi LN, Kareem RS, Carter K, Ziehl P. Energy and CO2 emission assessments of alkali-activated concrete and Ordinary Portland Cement concrete: A comparative analysis of different grades of concrete. Cleaner Environmental Systems. 2021;3:100047.
[29] Wajima T, Matsuka S. A new recycling process of waste glass wool using pyrolysis with sodium hydroxide. International Journal of Chemical Engineering and Applications. 2019;10:75-9.
[30] Saptamongkol A, Sata V, Wongsa A, Kroehong W, Ekprasert J, Chindaprasirt P. Hybrid geopolymer paste from high calcium fly ash and glass wool: Mechanical, microstructure, and sulfuric acid and magnesium sulfate resistance characteristics. Journal of Building Engineering. 2023;76:107245.
[31] Lemougna PN, Adediran A, Yliniemi J, Ismailov A, Levanen E, Tanskanen P et al. Thermal stability of one-part metakaolin geopolymer composites containing high volume of spodumene tailings and glass wool. Cement and Concrete Composites. 2020;114:103792.
[32] Noh S, Park N, Kwon O, Lee J. A study on the mechanical properties of impermeable asphalt using waste glass wool. Journal of the Korean Asphalt Institute. 2020;10:1-13.
[33] Santos NAd, Vieira PLC, Araujo GS, Louzada DM, Lima MBd, Sagrillo VPD. Cement plate slab production with the incorporation of glass wool waste ground. REM-International Engineering Journal. 2018;71:75-80.
[34] Rodrigues G, Alves J, Espinosa D, Tenorio J. Insertion of marble waste in the production chain of glass wool.
[35] dos Santos LF, de Carvalho JMF, Peixoto RAF, Brigolini GJ. Iron ore tailing-based geopolymer containing glass wool residue: A study of mechanical and microstructural properties. Construction and Building Materials. 2019;220:375-85.
[36] Kozub B, Bazan P, Gailitis R, Korniejenko K. Mierzwi nski, D. Foamed Geopolymer Composites with the Addition of Glass Wool Waste. Materials 2021, 14, 4978. s Note: MDPI stays neutral with regard to jurisdictional claims in published …; 2021.
[37] Vieira P, Santos N, Louzada D, Araujo G, Della V. Reuse of waste of glass wool in the production of mortar.
[38] Bae J-H, Oh J-H, Byun J-S, Lee J-M. Experimental Study of Thermal Conductivity for Glass Wool by Inserted Dissimilar Materials based on Structural Composites. Journal of the Society of Naval Architects of Korea. 2018;55:448-55.
[39] Kraševec B, Thara PBY, Tiyyagura RH, Muhič S. Prediction of binder polymerization rate in the glass wool curing oven. Thermal Science. 2024:139-.
[40] Thirukumaran M, Kannan LV, Sankar I. Study on mechanical properties of glass wool/epoxy reinforced composite. International Journal of Computer Aided Engineering and Technology. 2018;10:15-25.

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[41] Ferrández D, Álvarez M, Saiz P, Zaragoza-Benzal A. Recovery of mineral wool waste and recycled aggregates for use in the manufacturing processes of masonry mortars. Processes. 2022;10:830.

[42] ASTM Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens); C109/C109M-12; ASTM International: West Conshohocken, PA, USA, 2012.

[43] Benmansour N, Agoudjil B, Gherabli A, Kareche A, Boudenne A. Thermal and mechanical performance of natural mortar reinforced with date palm fibers for use as insulating materials in building. Energy and Buildings. 2014;81:98-104.

[44] Al-Obaidy AS, Sarsam KF, Karim AKA. Strengthening of Ferro-cement Beams in Torsion by CFRP Strips. Eng & Tech Journal. 2014;32.

[45] Ahmad J, González-Lezcano RA, Majdi A, Ben Kahla N, Deifalla AF, El-Shorbagy MA. Glass fibers reinforced concrete: Overview on mechanical, durability and microstructure analysis. Materials. 2022;15:5111.

[46] ASTM Standard C496. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

[47] ASTM C78, Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading, ASTM C78-02, Philadelphia, PA, USA, 2002.

[48] Büyükkürkçü H, Durmuş A, Çolak H, Kurban R, Şahmetlioğlu E, Karaköse E. Investigation of the performance and properties of ZnO/GO double-layer supercapacitor. Journal of Physics and Chemistry of Solids. 2024;191:111984.

[49] Gebremariam AT, Vahidi A, Di Maio F, Moreno-Juez J, Vegas-Ramiro I, Łagosz A et al. Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes. Construction and Building Materials. 2021;273:121697.

[50] Mrema AH, Noh S-H, Kwon O-S, Lee J-J. Performance of glass wool fibers in asphalt concrete mixtures. Materials. 2020;13:4699.

[51] Aytekin O, Kurban R, Durmuş A, Çolak H, Karaköse E. Investigation of the structural and magnetic properties of rapidly solidified Nd–Fe–B–Ce alloys. Journal of Materials Science: Materials in Electronics. 2024;35:1485.

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