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Research article

Sustainable translucent geopolymer concrete based on metakaolin and recycled glass

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Abstract: In this study, a new translucent geopolymer concrete (TGPC) was developed using recycled crushed glass as a partial fine aggregate substitute and metakaolin as the only binder to combine sustainability with architectural functionality. This paper presents an eco-innovative system that simultaneously optimizes the structural, optical, and thermal properties, in contrast to traditional translucent concrete that uses Portland cement and virgin optical fibers. Alkali-resistant glass fibers (ARGF), coated and uncoated optical glass fibers (OGF), and crushed glass (0–60%) were included in different amounts in the six mix designs. Extensive tests were performed, including scanning electron microscopy (SEM) microstructural analysis, light transmittance, thermal conductivity, compressive strength, and flexural strength. The optimum proportion (T3), based on the data obtained, reached a unique synergy between strength, transparency, and thermal insulation with a compressive strength of 35.8 MPa, bending strength of 5.0 MPa, light transmission of 2.2%, and lower thermal conductivity of 0.686 W/m·K. Based on the SEM analysis, early interface degradation was noted on the uncoated fibers, but the fluoropolymer-coated OGF retained robust fiber-to-matrix adhesions. This work is original in the context of the first study that employed a unique combination of recycled glass materials, fluoropolymer-coated fibers, and a metakaolin binder with lower carbon emissions. These data show that TGPC is an alternative material suitable for ecologically concerned and energy-efficient daylighting architectural technologies.

Keywords: translucent concrete; light transmittance; metakaolin binder; thermal conductivity; sustainable construction

1. Introduction

Translucent concrete is a completely fresh construction material that combines functionality and aesthetic appeal because it can transmit light through concrete. The peculiar feature of translucent concrete is its ability to introduce natural light through the construction material, which lessens the need to use artificial lighting and helps design buildings in an energy-efficient manner. Furthermore, it increases the aesthetic appeal of the interiors of buildings. It is due to this that translucent concrete is increasingly being applied in facades, walls, pavements, and decorative structural elements. This is more so in the field of sustainable and green architecture, where the design of natural sunlight is of great importance for reducing energy consumption [1–4].

Despite these advantages, there are several environmental and practical issues associated with standard translucent concrete systems. The majority of reported techniques employ Portland cement as the primary binder and considerable quantities of new optical fibers or specially produced clear aggregates. Portland cement production consumes much energy and emits approximately 8% of CO_2 in the world, which poses significant difficulties concerning sustainability [5,6]. It is also more complex, as the process of creating them is more complicated, and installing optical fibers makes them very expensive. Therefore, it is not yet clear whether traditional translucent concrete will prove to be eco-friendly and cost-effective in the future. This restricts its application in environmentally friendly construction.

Geopolymer binders are one of the methods that could help overcome these challenges because they are environmentally friendly alternatives to Portland cement. Geopolymer binders are alkaline activated by aluminosilicate precursors. Geopolymer binders are known for their lower carbon footprint, higher chemical resistivity, and improved mechanical performance [6,7]. Metakaolin is a preferred precursor for geopolymers because of its high purity, consistent chemical composition, and pozzolanic nature. Thus, it is easy to develop high-density aluminosilicate cements [5,8,9]. The properties of fly ash are highly variable depending on their sources, whereas metakaolin geopolymers are highly replicable and reliable; thus, they are an excellent choice for both functional and architectural concretes [10].

Together with the production of eco-friendly binders, the use of recycled aggregates has become popular once again because of the eco-friendliness of concrete materials. The use of recycled crushed glass, which can be used instead of natural aggregates, has several advantages, including the fact that it is easy to obtain, does not produce any waste materials in landfills, and has natural optics [11,12]. Graded glass particles can function as micro inclusions for light scattering or light guidance. This enables light to pass through hardened concrete [4,13].

In addition, glass aggregates tend to be less thermally conductive than normal mineral aggregates, which can enable concrete elements to retain heat better [2,3].

In the case of the passage of light through translucent concrete, everything is a question of the interaction of the binder matrix, aggregates, fibers, and internal interfaces. Light is principally propagated by optical glass fibers via total internal reflection. In contrast, crushed glass particles scatter or diffuse light depending on the size, shape, and quality of the interface [3,4]. However, the success of such systems is highly reliant on the clarity of the binder matrix, performance of the fiber-matrix interfacial transition zone (ITZ), and ability of the fibers to perform in very alkaline environments. Unprotected optical fibers can be interracially degraded in geopolymer systems because of the alkaline environment, which can cause mechanical degradation and optical disconnection [6,14].

Although numerous researchers have investigated the use of translucent concrete produced using Portland cement or several other popular binders, not much research has been conducted on the use of translucent geopolymer concrete. Existing literature has mainly focused on the installation procedures of optical fibers, cement-based matrices, and aesthetic performance, and not much has been done with regard to environmental considerations and multifunctional performance [3,4]. In addition, the literature on recycled glass aggregates has been mostly dedicated to either mechanical or durability properties, usually with no extensive examination of their collective optical and thermal properties [11–13]. The synergistic use of geopolymer binders based on metakaolin, recycled crushed glass aggregates, and optical glass fibers under different surface conditions (coated and uncoated) has not been appropriately explored. Moreover, there is still no proper understanding of the correlation between the mechanical strength, light transmittance, and thermal conductivity of these systems [1,2,4].

The objective of this work is to design and experiment with the development of a sustainable translucent geopolymer concrete (TGPC) that utilizes metakaolin as the sole binder and recycled crushed glass as a partial substitute for fine aggregates.

This study systematically investigates the influence of alkali-resistant glass fibers (ARGF) and optical glass fibers, both coated and uncoated, on compressive strength, bending strength, light transmission, and thermal conductivity. In addition, this research incorporates scanning electron microscopy (SEM) to investigate the microstructural properties of the fiber/matrix and glass/matrix interfaces. This project seeks to remedy the design of a process to produce load-carrying and energy-efficient translucent concrete to be used in building structures. In addition, this project seeks to reduce the use of low-carbon materials with functionality criteria for different functions.

2. Materials and methods

This section presents the materials and experimental techniques used to create translucent geopolymer concrete. In addition to providing comprehensive descriptions of the mix design, casting, curing, and technical data of the essential components, it lists the types and specifications of the raw materials, such as binders, activators, aggregates, and fibers. This study emphasizes the creative application of alkali-resistant fibers, both coated and uncoated, and post-consumer crushed glass.

2.1. Materials

To satisfy both structural and optical requirements, the translucent geopolymer concrete developed in this study requires carefully selected high-performance raw materials. High purity metakaolin from BASF (Germany) was the main binder used; it had a median particle size (d50) of approximately 3 μm, whiteness of over 85%, silica content of over 52%, and alumina content of over 40%. To guarantee high pozzolanic reactivity, metakaolin was thermally activated at 750 °C. A 10 molar sodium hydroxide solution made from analytical-grade (purity ≥ 98%) pellets from Merck (Germany) and a sodium silicate solution (Type N) from PQ Corporation (USA) with a solid content of 45% and a SiO_2/Na_2O ratio of approximately 2.5 were used as the alkaline activator system.

A combination of natural silica sand and crushed glass from Reglass Recycling Ltd. was used as fine aggregates. The colorless glass was cleaned, dried, and sieved to remove particles smaller than 1.2 mm. The percentages of glass replacement by mass were 0, 20, 40, and 60%. Two types of fibers were added for mechanical reinforcement and light transmission: optical glass fibers (OGF) with diameters of 1 mm and lengths of 10 cm were horizontally embedded in the matrix. Commercially available fluoropolymer-coated fibers, such as FEP-coated silica fibers from Thorlabs Inc. and OFS Fitel LLC (USA), which provide excellent chemical resistance and stable light transmittance, were used to withstand the extremely alkaline environment of the cell. Furthermore, to increase the flexural and tensile strengths, ARGF were introduced under the trade name SikaFiber® AR (Sika AG, Switzerland). These fibers contained at least 16% zirconia (ZrO_2) and were 6 mm long and 14 µm in diameter, respectively. An alkaline solution was prepared using water as the solvent. A low-concentration polycarboxylate ether (PCE)-type superplasticizer was used as an additive for better workability without affecting the optical transparency. This additive was used at a concentration of 1.0% of the binder weight for workability while maintaining light transmittance. The additive had a density of 1.05 g/cm^3 and was a light liquid. This is evident in Figure 1, which shows the nature and form of the substances.

Figure 1. Materials used in this study, including: (a) metakaolin; (b) crushed recycled glass; (c) ARGF; and (d) both coated and uncoated optical glass fibers.

2.2. Preparation of samples

A list of full mix quantities is presented in Table 1. To clarify matters, however, all mixes contained a fixed amount of binder at 450 kg/m^3, and there was also a fixed activator-to-binder ratio. The quantities of recycled glass and fibers were varied and altered in this experiment. A superplasticizer based on polycarboxylate ether was added to all mixtures at a constant level of 1 wt.%

based on the binder's weight to ensure workability and did not damage the optical properties. In addition, a constant molar concentration of 10 M sodium hydroxide aqueous solution was used for all mixtures to ensure that the conditions were the same for alkaline activation.

Table 1. Mixtures used in this study.

Mix ID	Metakaolin (kg/m^3)	Sand (kg/m^3)	Recycled glass (%)	Na_2SiO_3/NaOH	ARGF (%)	OGF (vol%)
T1	450	1350	0	2.5	0	0
T2	450	1080	20	2.5	0	3
T3	450	810	40	2.5	0.5	3
T4	450	540	60	2.5	1.0	4
T5	450	810	40	2.5	0.5	3 (uncoated)
T6	450	540	60	2.5	1.0	4 (uncoated)

The mixing and casting processes were designed to maintain the optical channels created by the embedded fibers, as well as to ensure that the particles were evenly dispersed. To create a homogenous paste, all the dry ingredients, metakaolin, natural sand, crushed glass, and ARGF, were combined using a planetary mixer for two minutes. To permit stabilization, an alkaline activator solution made up of sodium hydroxide and sodium silicate was prepared 24 h prior to mixing. This solution was slowly introduced into the dry mix together with the PCE-based superplasticizer during blending so that there would be no segregation and the workability would be constant. The fibers in the mixes with OGF were laid manually in horizontal arrays in the molds to maximize the transmission of light. Casting was performed in standard steel molds of the requisite dimensions to suit different tests; that is, 50 mm thick slabs to test thermal and optical analysis, 100 mm cubes to test compressive strength, and 100 × 100 × 400 mm prisms to test flexural strength and light transmittance. All samples were mixed using a vibrating table to remove air bubbles. The mixing technique was amended and modified according to previous techniques used in studies involving geopolymers to add optical fibers and maintain the uniformity of the mixture [5]. To achieve perfect geo-polymerization and maintain the optical properties of the translucent paste, a two-step curing method was followed. The specimens underwent casting and were placed in a humidity chamber, and the chamber was heat-cured for 24 h at 60 °C. The initial heating process advanced the premature stage of the matrix and aluminosilicate dissolution. After demolding, the specimens were cured for 28 d at 23 ± 2 °C and 60% relative humidity. This longer curing period reinforced the interfacial bond between the matrix and fibers; the optical pathways required to transmit light and the geopolymer network gradually densified with time. This study selected a curing process that was similar to the procedures in the past research on geopolymer systems founded on metakaolin [10].

2.3. Methods of testing

The mechanical, optical, and thermal properties of the translucent geopolymer concrete were determined using various standardized and specifically developed testing methods.

Compressive strength tests were performed on 100 mm cubic specimens as per ASTM C39 [15]. The specimens were tested using a universal testing machine at a loading rate of 0.5 MPa/s following 28 d during the curing period. All tests were considered with an average of three specimens in a mix to ensure statistical reliability.

The flexural strength was measured using prismatic specimens of 100 × 100 × 400 mm in accordance with the ASTM C78 guidelines [16]. A three-point loading setup was used to determine the modulus of rupture (MOR). This experiment was necessary to determine the effects of alkali-resistant glass fiber reinforcement.

The light transmittance was measured in two complementary ways. First, a digital lux meter was used to measure the intensity of the light passing on the slab samples of 50 mm thickness. The slabs were placed in a dark room between the meter and the controlled source of light. Second, pixel intensity maps and grayscale distributions were used to analyze the images of the illuminated specimens to assess the uniformity, clarity, and patterns of light distribution. This experimental arrangement relied on the experimental procedures of past translucent concrete research because there are no standardized ASTM protocols for cementitious light-transmitting substances. First, a digital lux meter was used to measure the intensity of the light passing on the slab samples of 50 mm thickness. The slabs were placed in a dark room between the meter and the controlled source of light. Second, pixel intensity maps and grayscale histograms were applied to the images of the illuminated specimens to assess the uniformity, clarity, and patterns of light distribution.

The thermal conductivity was measured using the guarded hot plate method according to ASTM C177 [17]. The 50 mm thick disc specimens were tested at steady-state temperatures. The test was used to identify the influence of porosity and glass inclusions on the insulation properties of concrete.

Bending SEM was employed to determine the microstructure and pore distribution, as well as interfacial bonding between the embedded fibers and the matrix. In preparation for imaging, samples of individual mixtures, especially those of uncoated OGF, were sectioned, dried, and gold coated. SEM analysis was used to obtain information about filler dispersion, densification of the matrix, and fiber degradation.

3. Results and discussion

In this section, the experimental results of the translucent geopolymer concrete mixture are described and shown. Note that the results are the averages of the three samples, and the error bars represent the standard deviation. In the discussion, the impact of varying amounts of glass, the type of optical fibers (coated or uncoated), and the dose rates of the fibers on the thermal conductivity, compressive strength, flexural strength, or light transmittance properties will be discussed. Interpretations were based on the fiber-matrix interaction, composition of the mixture, and effectiveness of the fiber coatings. In addition, SEM analyses were performed to assess durability. The performance and novelty of the newly designed mixes were verified by comparison with the reference translucent mixes and normal concrete. The results in Table 2 and Figures 2–6 explain the quantitative comparison among the six mixes (T1–T6). Error bars in the graphs denote the standard deviation (SD).

Table 2. Experimental results for translucent geopolymer concrete.

Mix ID	Compressive strength (MPa)	Flexural strength (MPa)	Light transmittance (%)	Thermal conductivity (W/m·K)
T1	36.7	4.1	0	0.732
T2	34.3	4.5	2.4	0.715
T3	35.8	5	2.2	0.686
T4	33.4	5.3	2	0.661
T5	33.8	4.8	1.7	0.677
T6	31.5	5	1.2	0.652

3.1. Compressive strength discussion

Table 2 and Figure 2 illustrate the compressive strength values for the translucent geopolymer concrete mixtures, which varied from 31.5 MPa (T6) to 36.7 MPa (T1). Notably, the mix without fibers and recycled glass (T1) exhibited the highest compressive strength. Indeed, the results agree with previous studies suggesting that enhanced matrix integrity and compressive strength are normally gained in pure metakaolin geopolymer matrices because of the formation of a dense aluminosilicate gel network, free from the hindrances caused by inert adulterants, such as fibers and recycled glass [5,9,18–20].

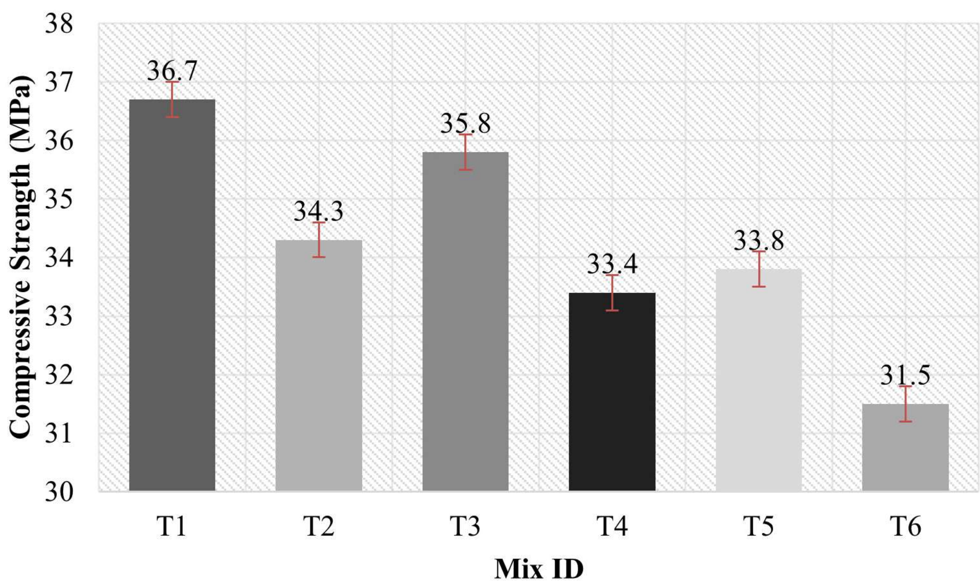

Figure 2. Outcomes of the compressive strength test.

Mixes T2 to T4 indicated a slight reduction in compressive strength with the addition of 20% to 60% recycled crushed glass was used as an aggregate. For instance, mix T4 (60% glass) had a compressive strength of 33.4 MPa, which indicated a slight reduction of around 9% compared to the reference mix without recycled waste glass. The major factor contributing to this reduction was the properties of the ITZ formed around the recycled glass and geopolymer paste mixture. The recycled glass had a smooth surface with limited interaction with the aluminosilicate gel, leading to a weak mechanical lock and chemical bonding between those materials. Further SEM analysis revealed the formation of small microvoids, which were also weakly bonded, at the interfaces between the recycled glass particles and geopolymer matrices, resulting in a reduced density of ITZ formation. These results depicted a slight diminishing compressive strength with an increase in the amount of recycled waste glass added, which can be attributed to a deficiency in stress transfer across those interfaces owing to compressive loading, as reported elsewhere [4,10]. Nonetheless, the results were well within the limits previously reported for waste glass addition to alkali-activated binders [8,18].

Mix T3 (40% glass + 0.5% ARGF + 3% OGF) had a compressive strength measured at a value of 35.8 MPa. The compressive strength recorded for mix T3 was almost similar to that recorded for mix S. Mix S is a mix that does not have any added components. The effect that the inclusion of ARGF had on the mix can be noted as reducing the effect that the interfaces between the glass aggregates had on the strength. ARGF fibers are useful in the mechanism that holds bridging between cracks. They allow easy flow between microcracks in a geopolymer matrix [1,6]. Studies have established that the inclusion of ARGF at a moderate level enhances the toughness rather than affecting the compressive strength [7,9,21].

Mixes T5 and T6, on the other hand, were found to have lower compressive strength values because their OGF was not coated. mix T6 exhibited the lowest values, which were measured to be 31.5 MPa. The SEM results confirmed the presence of smaller flaws at the interface of the uncoated fibers. This observation confirmed that the fibers were weaker owing to reactions with the alkaline compounds during the early stage, instead of decomposing entirely. These flaws on the surface may have contributed to the creation of microcracks and difficulty in stress transfer, especially under compressive loads. This observation can be confirmed by the fact that silica fibers were found to be susceptible to high pH values [14,22].

The role of sodium hydroxide and sodium silicate-activated geopolymer matrix cannot be overrated because it contributed to increasing strength through the formation of dense aluminosilicate gels. Excessive amounts of glass or uncoated fibers could result in a less dense matrix in some places, which could further impact the compressive strength [10,11].

All the TGPC mixes exhibited good structural properties for building construction because their compressive strength exceeded 30 MPa. It can be seen that there exists the possibility of balancing the properties of both mechanical strength and optical functionality in an optimum manner by choosing appropriate materials, mainly by adjusting the amount of glass and optical fibers that are resistant to alkali and are coated.

3.2. Flexural strength discussion

The flexural strength is a crucial indicator of the ability of a concrete material to withstand tensile stress and crack propagation under bending. Control mix T1 exhibited a flexural strength of 4.1 MPa, as shown in Table 2 and Figure 3, the addition of OGF resulted in a moderate increase in the flexural capacity. Mix T2 (3% coated OGF, 20% glass) achieved 4.5 MPa, whereas mix T3 (3% coated OGF, 40% glass replacement, and 0.5% ARGF) achieved 5.0 MPa. This implies that the coated OGF and ARGF may complement each other to improve tensile resistance and crack bridging.

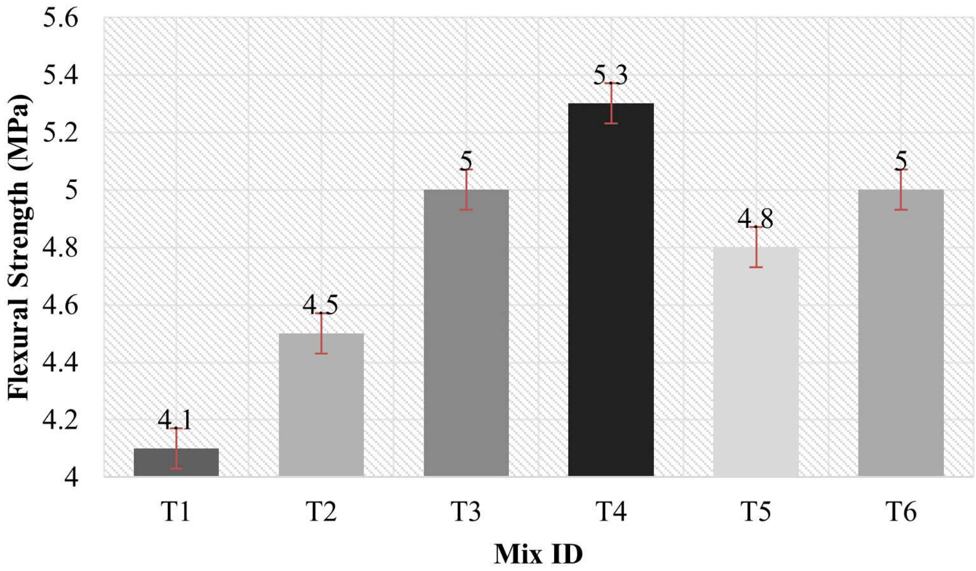

Figure 3. Outcomes of the flexural strength test.

The maximum flexural strength (5.3 MPa) was observed in T4, which contained 1.0% ARGF, 60% glass, and 4% coated OGF. The improved fiber-matrix interaction and fiber arrangement might be attributed to the increased mechanical strength observed. Although the coated OGF prevented the deterioration of the alkaline geopolymer matrix, the zirconia-based ARGF could play an important role in restricting the development of microcracks. As mentioned in previous research, ARGF can contribute to enhanced flexural strength without compromising durability [7,9].

Mixtures T5 and T6 (with uncoated OGF) showed slightly lower flexural strengths of 4.8 and 5.0 MPa, respectively, despite having comparable or higher fiber contents. Some imperfections at the interface and partially debonded regions were found by SEM observation, which could have influenced the efficiency of the interface in controlling cracks and stress transfer. Nevertheless, throughout the 28-day test period, no obvious indication of chemical degradation was observed in the samples. These findings highlight the significance of fiber-matrix compatibility and surface protection for durability and mechanical performance [6,14].

Furthermore, hybrid reinforcement is produced by combining OGF and ARGF, where OGF promotes light transmittance, and ARGF helps with crack control and post-crack strength. Aashaq and Zia [8] and Nasr et al. [1] have both suggested similar hybrid approaches to maximize the mechanical and functional qualities of sustainable concrete.

The above-described mechanics can be explained by analyzing the synergistic action of the fiber bridging mechanism and properties of the ITZ. In the case of compressive loading, the dominant parameters responsible for the determination of the mechanical properties are the improvement brought about by the matrix compaction and the effectiveness of the stress transfer in the aggregate-matrix and fiber-matrix interfaces. However, because the use of recycled glass reduces the strength of the ITZ regions, the value of the compressive strength is decreased by a small margin because of the inefficient transfer of the forces. The addition of ARGF increases the effectiveness of the crack-bridging mechanism.

The role of the fiber is more significant in the case where flexural loading is involved owing to the significance of the tensile stress. The bridging effect of the fibers prevents the opening up of microcracks, thereby making the material more resistant to stress, especially after the material has undergone cracking. The bonding between the coated optical fiber and geopolymer matrix was stronger than that between the uncoated fiber and geopolymer matrix. This results in efficient stress transfer, making the material more resistant to flexural strength. The weaker bonding between the uncoated fiber and the material results in debonding, hence the reduction in flexural strength with increasing amounts of fiber.

In conclusion, the findings indicate that fiber type and dosage affect flexural strength. Transparent geopolymer concrete with acceptable mechanical performance can be developed by combining moderate to high levels of ARGF with optical fiber coated with a transparent geopolymer coating.

3.3. Light transmittance discussion

Following the light transmittance data summarized in Table 2 and Figure 4, the fiber-reinforced translucent mixes showed a noticeable increase compared to the control mix (T1), which did not allow light to pass through (0.0%). Mix T2 had the greatest transmittance (2.4) and the highest ratio of glass aggregates (20%) and ratio of coated OGF (3%). This enhancement, as explained by Chiadighikaobi et al. [4], could be attributed to the relatively homogeneous dispersion and orientation of the fibers, which could act as partial waveguides that enable light to propagate through the matrix with less scattering.

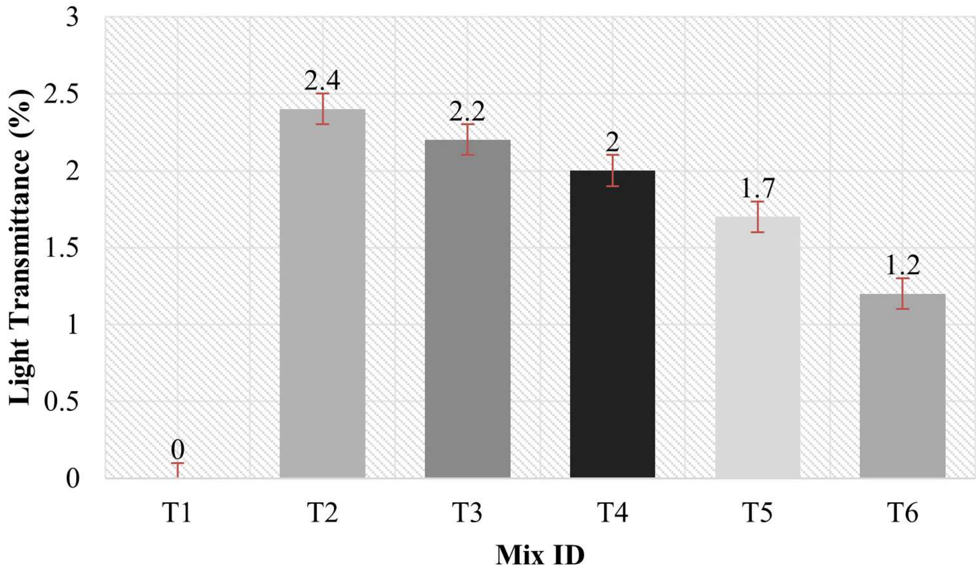

Figure 4. Outcomes of the light transmittance test.

When the proportion of glass rose to 60, there was a small drop in the transmittance of mix T4 (2.0), which was probably due to the higher heterogeneity and interfaces that promoted internal scattering. Such findings are related to the results obtained by Ling et al. [13], who concluded that SCC with increased glass content was less transparent.

Further reduction in light transmission was observed in mixtures T5 and T6, which included uncoated optical fibers (1.7% and 1.2%, respectively). In addition, the initial imperfections at the interfaces of the fibers, which are uncoated, and the alkaline environment may result in higher scattering and thus slightly low continuity. However, the light guidance function offered by the fibers was maintained after 28 days. Furthermore, these results are confirmed by SEM micrographs and are consistent with previous findings related to durability issues in comparable confectionery products [6,14].

The implication of these findings is that optical clarity is optimized by covering the fibers and ensuring that there is continuity in the interface between the fibers and the matrix. Nasr et al. [1] had highlighted the importance of interface engineering in functional construction materials, specifically in situations where there is double functionality related to mechanics and optics.

T2 and T3, which contain coated optical fibers and a moderate quantity of glass, were the tested mixes, and they exhibited a good compromise in light transmittance as well as mechanical performance. The next direction of work can be the creation of alkali-resistant uncovered coatings with improved optical performance and optimization of the fiber orientation. Figure 5 shows a schematic process map of the light transmission process in the translucent geopolymer concrete, which encompasses ARGF, coated and uncoated optical fibers, and recycled glass particles. The recycled glass particles partially refracted the incident light once they penetrated the geopolymer matrix. Optical fibers transmit light through a process of total internal reflection that ensures the concentration of transmission with minimum scattering. On the other hand, the higher dispersion of light is a result of spaces or the absence of strong interfacial bonding surrounding the uncoated fibers. The advantages of using ARGF fibers include the following: they promote stronger mechanical strength of the matrix, indirectly contributing towards ensuring a clear optical path, despite not contributing towards the transmission of light.

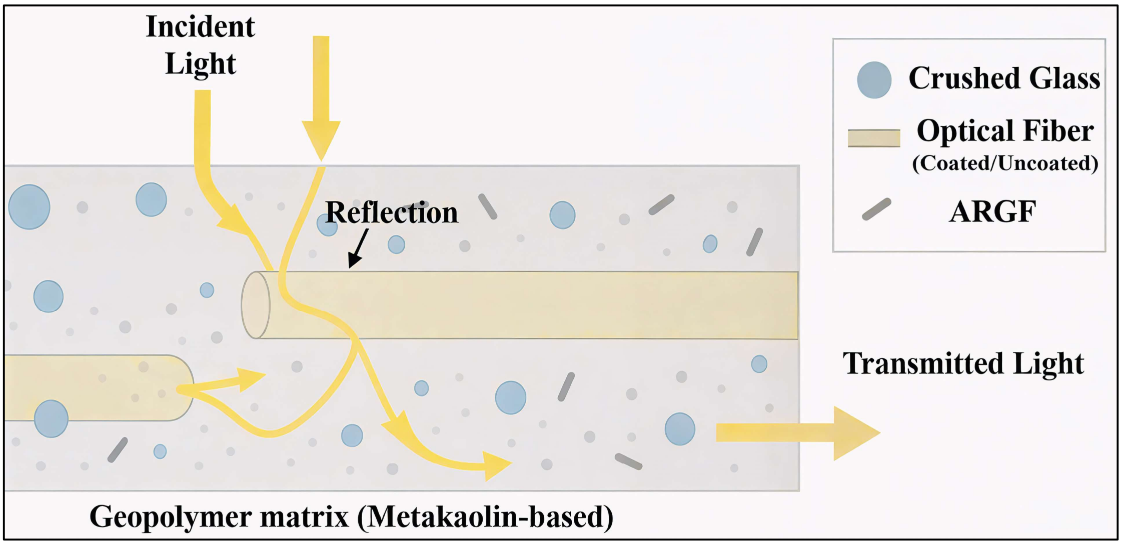

Figure 5. Schematic of the light transmission process using ARGF, coated and uncoated optical fibers, and recycled glass in translucent geopolymer concrete.

In the case of TGPC mixtures, there are lower values of light transmittance compared to translucent concrete systems made of Portland cement with optical fiber structures. This is mainly because a geopolymer has an opaque matrix with crushed glass, which scatters light rather than transmits it. The geopolymer has a denser aluminosilicate gel than cement, which has higher light absorbability. In contrast, light transmission is mostly dependent on optical fibers in cement-based translucent concrete.

Moreover, owing to the utilization of crushed glass as a partial substitute for aggregates, various glass matrix interfaces are created, which could have adverse impacts on reflection losses and internal scattering. Other studies have shown that specimens with geopolymers or modified materials, which are translucent, obtained lower light transmission values compared to those with fiber-dominated cementitious materials, despite the higher environmental value and heat retention. These results are comparable to the results achieved because of the utilization of the applied material design method.

However, it is worth pointing out that the degree of light transmittance achieved can be viewed as satisfactory for architectural lighting or artistic illumination, where soft or diffuse illumination is preferred over direct illumination.

3.4. Thermal conductivity discussion

The thermal conductivities of the translucent geopolymer concrete mixtures varied from 0.652 (T6) to 0.732 W/m·K (T1), indicating the effects of the fiber arrangement and glass particle content on the thermal conductivities. Among these, the reference mixture T1, which did not contain optical fibers or glass particles, recorded the highest value of thermal conductivity, as shown in Table 2 and Figure 6. As indicated in earlier studies, this can be attributed to the high-density matrix structure of the MK-based geopolymer binder, enabling the effective conduction of heat, as it contains a solid phase high in density, as reported in [2,5]. When crushed glass aggregates were added to mixes T2–T6, the thermal conductivity gradually decreased. The lower thermal conductivity of glass than that of conventional aggregates and the presence of irregular glass particles that block heat flow pathways could be the cause of this decrease [1,11]. T6 exhibited the lowest thermal conductivity (0.652 W/m·K), despite having the largest volumes of uncoated optical fibers and glass. Both the intrinsically low conductivity of glass fibers and the insulating effect of the surrounding micro-voids could be responsible for this [13].

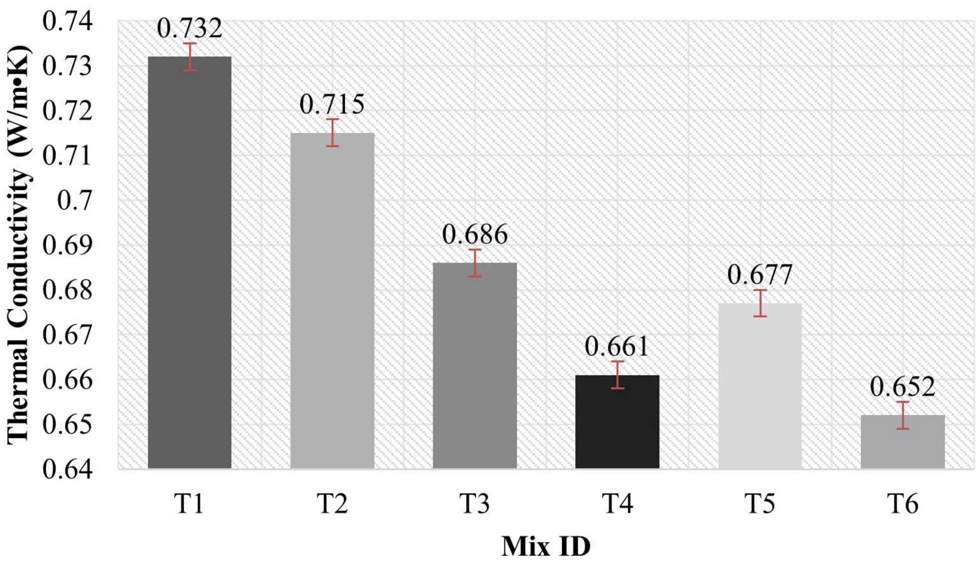

Figure 6. Outcomes of the thermal conductivity test.

Additionally, the slight differences between the mixes with uncoated (T5 and T6) and coated (T3 and T4) fibers imply that surface treatment may also affect heat conduction. While coated fibers guarantee more consistent bonding with the matrix, which lowers the interfacial thermal resistance, uncoated fibers typically encourage interfacial micro-gaps that improve insulation, as shown in Figure 7 [2,4].

These results are consistent with those of previous studies by Spanodimitriou et al. [2] and Nasr et al. [1], who noted that matrix discontinuity and internal scattering, respectively, may decrease the thermal conductivity of multifunctional composites with inclusions that display distinct thermal behaviors. Additionally, the addition of ARGF fibers improved the compactness of the matrix and inhibited the growth of microcracks, both of which indirectly supported the maintenance of more steady and uninterrupted heat pathways. Transparent geopolymer concrete appears to offer promising thermal insulation properties for energy-efficient building applications, as evidenced by the fact that all the developed mixes had thermal conductivities that were significantly lower than those of conventional concrete (typically 1.4–2.0 W/m·K) [12].

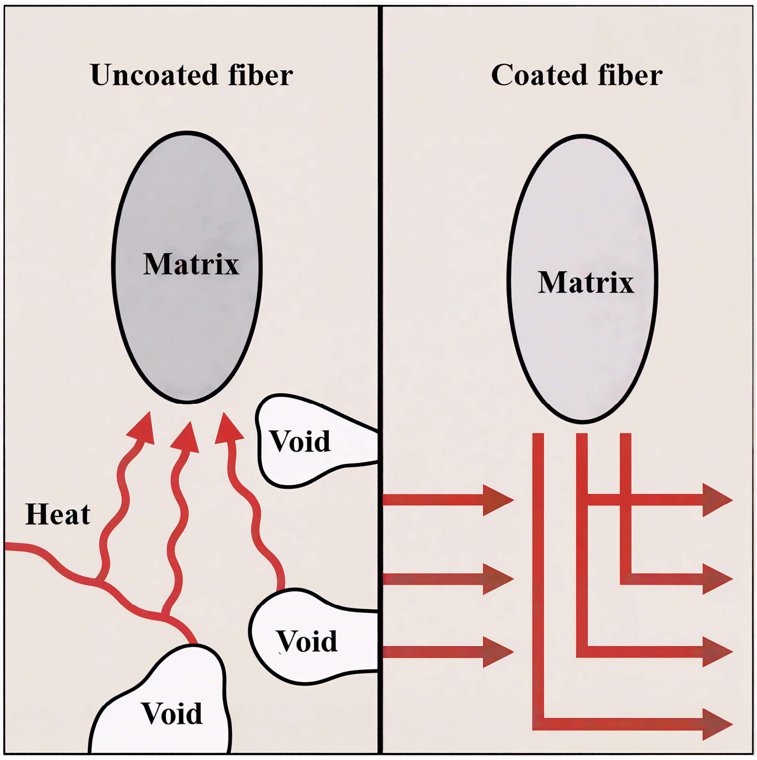

Figure 7. Coated fibers guarantee improved bonding and transfer, whereas uncoated fibers create voids that disperse heat.

3.5. SEM discussion

SEM observations provide the necessary microstructural information about the behavior of TGPC mixes, as they explain the role of the fiber-matrix and aggregate-matrix transition zones in shaping the observed macroscopic behavior [8,9]. The SEM micrographs make it clear that the integrity, continuity, and density of the ITZ determine the strength, optical performance of the composite as well as thermal behavior of geopolymer-based composites [2,6].

In the mixture of T3, where the OGF were coated, the fibers were uniformly filled throughout the geopolymer matrix and densely covered the interface with a continuous and well-adhering interface with no visible voids, debonding, or surface degradation (Figure 8). This microstructure indicates that the fluoropolymer coating was effective in preventing alkaline attack on the fibers and in enabling bonding firmly between the fibers and the aluminosilicate gel structure. Protected fibers have been investigated using similar techniques to stabilize the interface in very alkaline cementitious and geopolymer matrices [7,14]. The development of a stable ITZ enabled the effective transfer of stress in the direction of mechanical loading, delayed the creation of microcracks, and decreased light scattering between interfaces, thereby explaining the significantly high compressive strength (35.8 MPa), flexural strength (5.0 MPa), and sustained light transmittance (2.2%) in this mix.

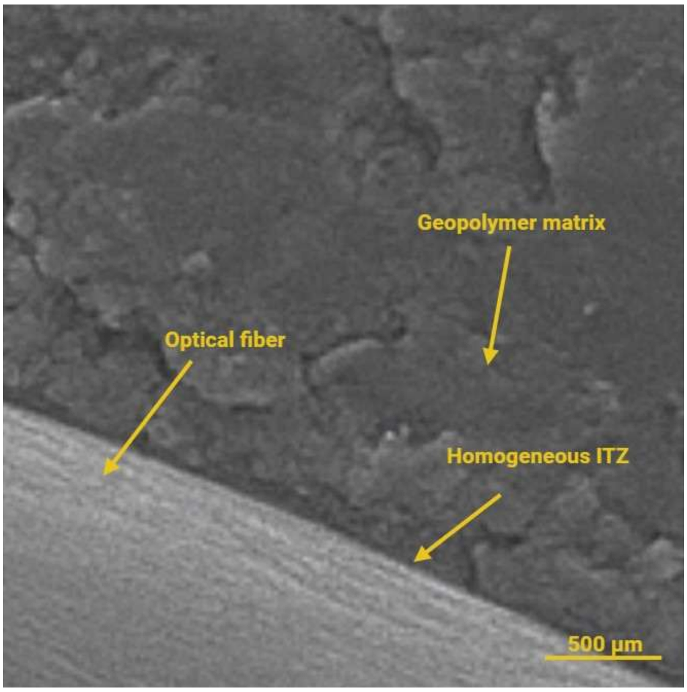

Figure 8. SEM micrograph of mix T3, where a silver-coated optical glass fiber is embedded in a geopolymer matrix, along with a dense homogeneous ITZ.

SEM images of mixes with uncoated optical glass fibers (such as T5 and T6) exhibited local interfacial defects, such as micro-voids, partial debonding, and early-stage surface defects at the fiber mesh boundary (Figure 9). No significant chemical degradation occurred after 28 days, although such indicators indicate that the geopolymer framework and unguarded silica-based fibers begin to react with the alkaline substances. Such loosely coupled regions have higher probabilities of initiating and propagating microcracks and therefore reduce the efficiency of stress transfer and increase light scattering within the material, as previously observed in silica fibers under high-pH conditions [10,14]. These imperfections at the interface are therefore what made the mixes with uncoated fibers have lower compressive strength (31.5–33.8 MPa), flexural strength, and light transmittance.

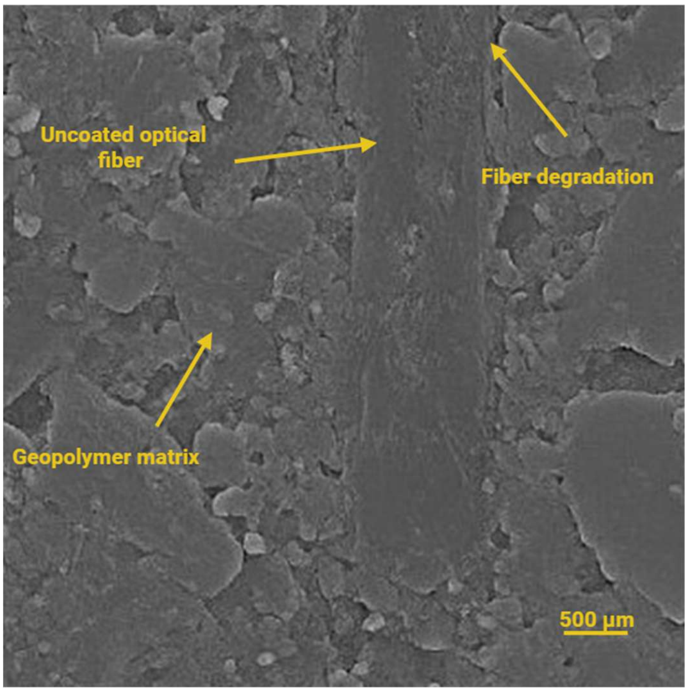

Figure 9. This shows the SEM image of mix T5, containing an uncoated optical fiber made of glass embedded in a geopolymer matrix, where the fiber/matrix interface has deteriorated.

The SEM test also highlights the importance of ARGF as a means of increasing the stability of the microstructure. According to Figure 10, ARGF fibers were strongly bonded to the geopolymer matrix through interfaces. This was revealed by the fact that it had very few microcracks and a tight ITZ. In addition to filling cracks, ARGF fibers facilitated the local matrix to be denser and more effective in redistributing stress, which directly resulted in the improved flexural performance observed in mixes containing ARGF. This tendency is consistent with previous studies, which revealed that fiber-reinforced alkali-activated materials are tougher or more favorable in terms of their post-cracking behavior [2,6].

The interfaces of the recycled crushed glass particles and geopolymer matrix were also relatively smooth, with small voids, which indicates that the mechanical interlocking process is not as strong as in the case of natural aggregates. These attributes confirm the creation of a reduced glass-matrix ITZ that controls stress transfer efficiency and explain the moderate loss in compressive strength with increasing glass content [4,10]. Simultaneously, having many glass–matrix interfaces enhances the number of internal reflection and scattering sites, which consequently influences the light transmittance and thermal conductivity by breaking the continuous optical and thermal transfer pathways [1,2].

The SEM observations conclusively demonstrate a structure-property relationship, meaning that mechanical strength, optical performance, and thermal behavior variations in TGPC mixes are largely dependent on microstructural properties and interfacial integrity, but not on composition. Such findings highlight the scientific significance of interface engineering to geopolymer-based translucent composites and confirm that controlling the quality of the ITZ through the use of the surface treatment of fibers and the choice of materials is essential to achieve a balanced multifunctional performance.

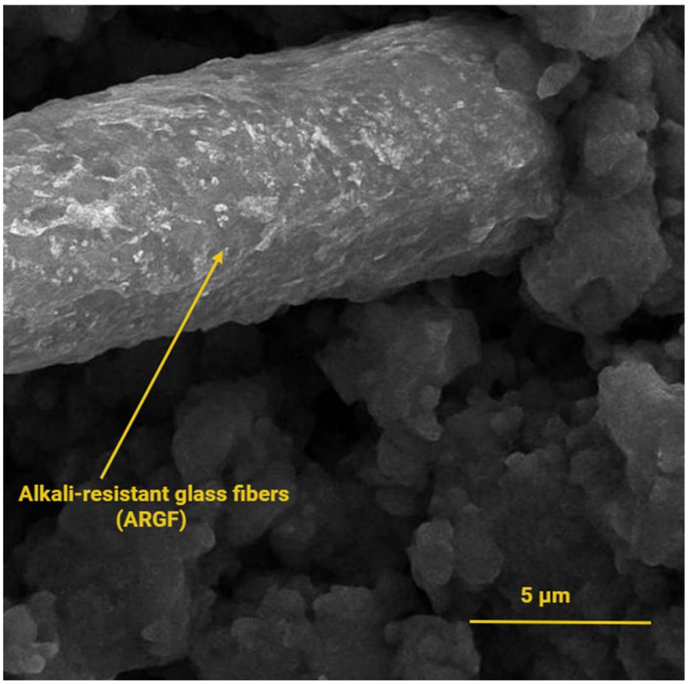

Figure 10. SEM image of mix with ARGF, where good bonding between fibers and geopolymer is observed.

4. Conclusions

This paper discusses the feasibility of developing sustainable TGPC with metakaolin as the only binder and recycled crushed glass as a partial binder replacement. We compared the performance of glass content, ARGF, and coated and uncoated optical glass fibers in the context of influencing mechanical, optical, and thermal performance.

The experimental results showed that all the TGPC mixtures achieved compressive strengths of more than 30MPa, and thus they were found to be structurally suitable in architectural applications. When recycled glass was added, the compressive strength decreased slightly. The reason behind This is because the glass particles and geopolymer matrix form a weaker ITZ between them. To this decrease, ARGF was added, and this lowered the drop by increasing crack bridging mechanisms and redistribution of stress.

Optically, the transmittance of light is less than that in conventional cement-based translucent concrete systems. This phenomenon could be explained by the increased light scattering at the interfaces of the glasses and the matrix and by the inherently high opacities of the metakaolin-containing geopolymer matrix. Nevertheless, even the achieved levels of light transmittance are decent in architectural daylighting and aesthetic applications, in which diffused light is commonly desirable.

Optical glass fibers were coated, resulting in improved mechanical and optical characteristics compared to uncoated optical glass fibers. This demonstrates the significance of the defense of fiber surfaces in geopolymer environments at a high level of alkalinity. In addition, by including recycled glass and geopolymer binders, the material became less thermally conductive, which may be beneficial for constructing energy-saving envelopes.

Overall, the findings indicate that judicious selection of materials and mix composition can be used to locate the optimal balance between mechanical stability, optical functionality, and thermal performance. The proposed TGPC system is an excellent low-carbon substitute for ordinary translucent concrete that is green. It is a mixture of sustainability and multipurpose performance that is used in high architecture.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Conceptualization: Rusul Ghadban and Lubna Kamil; methodology: Rusul Ghadban and Lubna Kamil; validation: Mohammed Abdulrehman and Samer Abdulhussein; formal analysis: Rusul Ghadban; investigation: Rusul Ghadban and Ali Flayyih; resources: Mohammed Abdulrehman; data curation: Rusul Ghadban and Ali Flayyih; writing, original draft preparation: Ali Flayyih and Mohammed Abdulrehman; writing, review and editing: Ali Flayyih and Mohammed Abdulrehman; visualization: Lubna Kamil; supervision: Mohammed Abdulrehman and Samer Abdulhussein; project administration: Mohammed Abdulrehman. All authors were actively involved in discussing the findings and refining the final manuscript.

Conflict of interest

The authors declare no conflicts of interest.

References

1. Nasr Y, El Zakhem H, Hamami AEA, et al. (2023) Comprehensive review of innovative materials for sustainable buildings' energy performance. *Energies* 16: 7440. https://doi.org/10.3390/en16217440
2. Spanodimitriou Y, Ciampi G, Tufano L, et al. (2023) Flexible and lightweight solutions for energy improvement in construction: A literature review. *Energies* 16: 6637. https://doi.org/10.3390/en16186637
3. Singh N, Colangelo F, Farina I (2023) Sustainable non-conventional concrete 3D printing—A review. *Sustainability* 15: 10121. https://doi.org/10.3390/su151310121
4. Chiadighikaobi PC, Adegoke MA, Kharun M, et al. (2023) A review of the structural properties of translucent concrete as sustainable material. *Open Constr Build Technol J* 17: e187483682681192. https://doi.org/10.2174/0118748368268119231003055958

5. Isah M (2025) Investigating the effects of metakaolin blended with sugarcane bagasse ash and rice husk ash based geopolymer on the engineering properties of geopolymer concrete. *Int J Adv Eng Manag* 7: 612–637. https://doi.org/10.35629/5252-0701612637
6. Wong LS (2022) Durability performance of geopolymer concrete: A review. *Polymers* 14: 868. https://doi.org/10.3390/polym14050868
7. Imtiaz L, Rehman SKU, Memon SA, et al. (2020) A review of recent developments and advances in eco-friendly geopolymer concrete. *Appl Sci* 10: 7838. https://doi.org/10.3390/app10217838
8. Aashaq IM, Zia ul Haq M (2024) A sustainable approach to geopolymer concrete utilizing waste materials including plastic waste. *AIP Conf Proc* 3050: 030005. https://doi.org/10.1063/5.0196296
9. Shaikh KS, Pachkar SS, Khan SA, et al. (2025) An experimental approach on the influence of addition of metakaolin on the properties of geopolymer concrete. *Int J Innov Eng Res Technol* 12: 1–10. https://doi.org/10.26662/ijiert.v12i6.pp1-10
10. Zhang S, Li Z, Ghiassi B, et al. (2021) Fracture properties and microstructure formation of hardened alkali-activated slag/fly ash pastes. *Cem Concr Res* 144: 106447. https://doi.org/10.1016/j.cemconres.2021.106447
11. Siddika A, Hajimohammadi A, Mamun MAA, et al. (2021) Waste glass in cement and geopolymer concretes: A review on durability and challenges. *Polymers* 13: 2071. https://doi.org/10.3390/polym13132071
12. Hamada H, Alattar A, Tayeh B, et al. (2022) Effect of recycled waste glass on the properties of high-performance concrete: A critical review. *Case Stud Constr Mater* 17: e01149. https://doi.org/10.1016/j.cscm.2022.e01149
13. Ling TC, Poon CS, Kou SC (2012) Influence of recycled glass content and curing conditions on the properties of self-compacting concrete after exposure to elevated temperatures. *Cem Concr Compos* 34: 265–272. https://doi.org/10.1016/j.cemconcomp.2011.08.010
14. Yusuf MO (2023) Bond characterization in cementitious material binders using Fourier-transform infrared spectroscopy. *Appl Sci* 13: 3353. https://doi.org/10.3390/app13053353
15. ASTM International (2023) Standard test method for compressive strength of cylindrical concrete specimens. ASTM C39/C39M-23. https://doi.org/10.1520/C0039_C0039M-23
16. ASTM International (2022) Standard test method for flexural strength of concrete (using simple beam with third-point loading). ASTM C78/C78M-22. https://doi.org/10.1520/C0078_C0078M-22
17. ASTM International (2023) Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus. ASTM C177-23. https://doi.org/10.1520/C0177-23
18. Ajayi B, Babafemi A (2024) Effects of waste plastic and glass aggregates on the strength properties of ambient-cured one-part metakaolin-based geopolymer concrete. *Appl Sci* 14: 1856. https://doi.org/10.3390/app14051856
19. Mehta S, Bhandari M (2021) Effect of glass fiber and recycled aggregates on geopolymer concrete. *IOP Conf Ser Earth Environ Sci* 889: 012038. https://doi.org/10.1088/1755-1315/889/1/012038
20. Qaidi S, Najm HM, Abed SM, et al. (2022) Concrete containing waste glass as an environmentally friendly aggregate: A review on fresh and mechanical characteristics. *Materials* 15: 6222. https://doi.org/10.3390/ma15186222

21. Srikrishna TC, Noolu V, Reddy BSK, et al. (2025) Investigations on mechanical and stress–strain characteristics of geopolymer concrete reinforced with glass fibers. *Sci Rep* 15: 6335. https://doi.org/10.1038/s41598-025-90752-3
22. Sharma U, Gupta N, Bahrami A, et al. (2024) Behavior of fiber-reinforced geopolymer composites: A review. *Buildings* 14: 136. https://doi.org/10.3390/buildings14010136