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REVIEW ARTICLE

A Review of the Structural Properties of Translucent Concrete as Sustainable Material

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Abstract:

This paper studies the production of sustainable and energy-saving concrete that can overcome the opaque nature of concrete with good strength properties. Consequently, this birthed translucent concrete. This study aimed to develop a detailed review of the properties and characteristics of translucent concrete, conduct some qualitative analysis on the concrete's potential light-transmitting abilities as well as its drawbacks and benefits translucent concrete, and make it accessible to scholars and researchers on this concrete type. The objective of this study was to review the properties of translucent concrete that have been studied by several researchers. To this study, it is believed that construction works with translucent concrete will be efficient and serve as a construction and economic breakthrough, specifically in low-income and low-middle-income nations where the cost of purchasing energy is high. A review assessment approach was used to examine past studies of translucent concrete with a focus on optic fiber since more than 80% of the available works documented employed optic fiber as the light-transmitting material. To achieve the objectives of this study, a review methodology was used. It was discovered that one of the limitations of translucent concrete is the production cost associated with the purchase cost of the optic fiber . A variety of restrictions and research gaps were found in the review study conducted on translucent concrete. One of the gaps identified was the strengthening of translucent concrete and the optical fiber percentage that could give a durable concrete mix. Another gap identified in the reviewed research study relates to tests aiming to identify the influence of dissimilar ratios of optical fibers on the material's strength and energy-saving properties. Some studies indicated the incorporation of optic fiber in concrete at a certain percentage improved the compressive strength of the concrete, while some researchers concluded that including optic fiber in the concrete decreased the compressive and flexural strength of the concrete. Low material strength and the determination of the ideal optic fiber ratio are the key constraints. This type of concrete can be implemented in building construction and walkways but is not limited to them. This present review study additionally identifies and suggests potential future research fields as well as offers ideas for filling up the known research gaps.

Keywords: Translucent concrete, Optical concrete, The strength of translucent concrete, Eco-friendly concrete, Sustainable concrete, Energy serving concrete.

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1. INTRODUCTION

Lately, sustainability in construction has been an alarming and growing matter globally and there's an urgent need to address it. Finding strategies and techniques to reduce energy use, environmental pollution, and building costs has recently become crucial [1]. The development of sustainable buildings has led the path to reduce the deterioration of energy and raw materials, which is crucial in protecting the environment. This invention has progressed and encouraged eco-friendly structure design and practices [2]. Since concrete is now the most frequently used material in the building sector [3, 4], it must be improved to support contemporary, sustainable, and environmental friendly properties [5]. Opaque concrete may be transformed into transparent concrete by fusing optical fibers with a concrete matrix. There are many different types of concrete, which are identified based on the composition, additives, surfaces, manufacturing technique, or type of reinforcing [6 - 10]. According to the type of concrete being used, some building components must be built or maintained differently. The concrete types can be differentiated according to several criteria: unit weight, compressive strength, application, and special properties. The concrete types are

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normal concrete, lightweight concrete, aerated concrete, heavy concrete, ultra-high-performance concrete (UHPC), water-impermeable concrete, waterproof concrete, self-compacting concrete, translucent concrete, refractory concrete, recycled concrete, concrete screed, prestressed concrete, textile concrete, fiber concrete, self-cleaning concrete, exposed (fair-faced) concrete, tamped or compressed concrete, amped or compressed concrete, sprayed concrete, vacuum concrete [10]. But light-transmitting concrete (LTC), also known as translucent or transparent concrete (TC), has captured the interest of global academics as well as concrete engineers owing to its relevance, practicality, and special qualities. Concrete is opaque because of its bulk and opaque particles and reinforcements, which prevent light from passing through. However, by incorporating optical fibers with a concrete matrix, opaque concrete might be changed into transparent concrete.

Embedded optical fibers, polymer resins, used glasses, or plastic pipes allow light to pass through translucent concrete (TC), a novel energy-efficient construction material, into the indoor space [11]. Translucent concrete is defined as concrete with the ability to transmit light from one end of its face to the other. Study [12] stresses the significance of innovative construction materials that can reduce the dependence on harnessing energy for artificial lighting. Their research attempts to ensure the construction of transparent concrete utilizing components that are easily accessible while making sure the required qualities aren't compromised. Among the numerous materials usually applied in non-structural walls of buildings, this material could also be applied. There are a number of benefits of translucent concrete, such as the provision of daylighting for buildings, good aesthetics, and the fact that it encourages the construction of green and sustainable buildings.

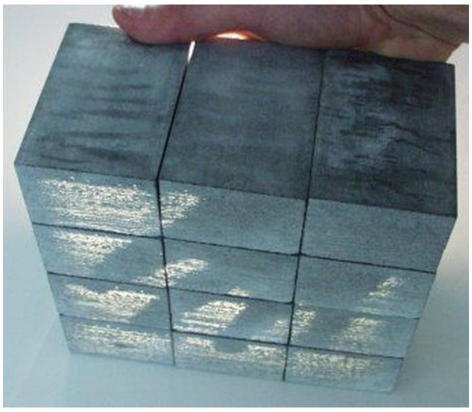

Fig. (1). LiTraCon block [16].

Transparent concrete, often known as translucent concrete, is a Canadian invention that was first introduced in 1935 and later enhanced by the addition of optical fiberglass [13]. In 1965, James N. Lowe of Britain created concrete wall panels that were installed on church walls and, by inserting stained glass pieces into the concrete mix, light penetrated the building [14]. By combining a significant amount of optical fiber with concrete, Aron Losonzi developed a new type of concrete known as LiTraCon (see Fig. **1**) for LiTraCon block), which was introduced as a patent in 2001. The composite was described as produced as a rigid and transparent concrete suitable for floors, sidewalks, and load-bearing walls [15], and the prototype of the translucent concrete panel was successfully developed in 2003 [2].

Since TC is a brand-new, environmentally-friendly building material, there is not much prior experimental research. The strength and light transmittance of plastic optical fibers (POF) with TC in them and having diameters of 0.3 mm, 0.5 mm, 0.75 mm, and 1.5 mm were examined by Altlomate *et al*. [17]. The findings demonstrated that the presence of POF had a varied impact on compressive strength (f_c). The direct ultrasonic pulse velocity (UPV) test result revealed that, despite the inclusion of POF, the quality of the TC was outstanding. The f_c and flexural strength (f_f) of cement-based polymethyl methacrylate (PMMA) fibers were investigated by Li *et al*. [18]. When the amount of fiber rose, both f_c and f_f of TC dropped. Additionally, none of the TC specimens had the same strength as the reference concrete; hence, adding PMMA fibers resulted in a decrease in f_c and f_f, notwithstanding the fibers' volume fraction. According to Li *et al*. [19], under different curing conditions, the f_c of sulfoaluminate cement-based TC linearly dropped as the number of optical fibers rose. Salih *et al*.'s [20] investigation of TC reinforced with POF and self-compacting mortar (SCM) was conducted. The f_c and f_f of TC were often reduced by the addition of POF. The strength characteristics of TC, however, appeared to be shifting in response to the fluctuation in diameter and volume of POF. In comparison to 1mm and 2mm diameter PMMA fibers, it was discovered that 2mm diameter PMMA fibers generated TC with a greater f_f and f_c. The evaluation of transparent concrete walls made using a random arrangement of optical fibers for application in Brazil's precast building was another study carried out by Tutikian and Marquetto [21]. The experimental findings showed that as the percentage volume of optical fibers grew, the f_c and tensile strengths (f_c) in the bending of TC dropped.

Research has confirmed that LTC is not only able to transmit light but also to reduce light energy utilization by up to 50% [22] without compromising its compressive strength. Previous investigations of the attributes of LTC found a variation in the translucent materials employed to manufacture LTC, which had a direct impact on the LTC's characteristics. Moreover, diverse emphases were placed on the assessment and parameters of LTC in previous studies based on the type of LTC and its applications.

LTC could be produced using a large number of translucent materials. However, optical fibers (OFs) made of waste glass and polymer resin are typically used. To produce LTC, materials with high translucency or high light transmittance can be used. Nearly no light is lost by optical fibers because the transmission of light through them is so bright and effective [15, 23 - 25]. The development of LTC is a great way to transmit light inside structures.

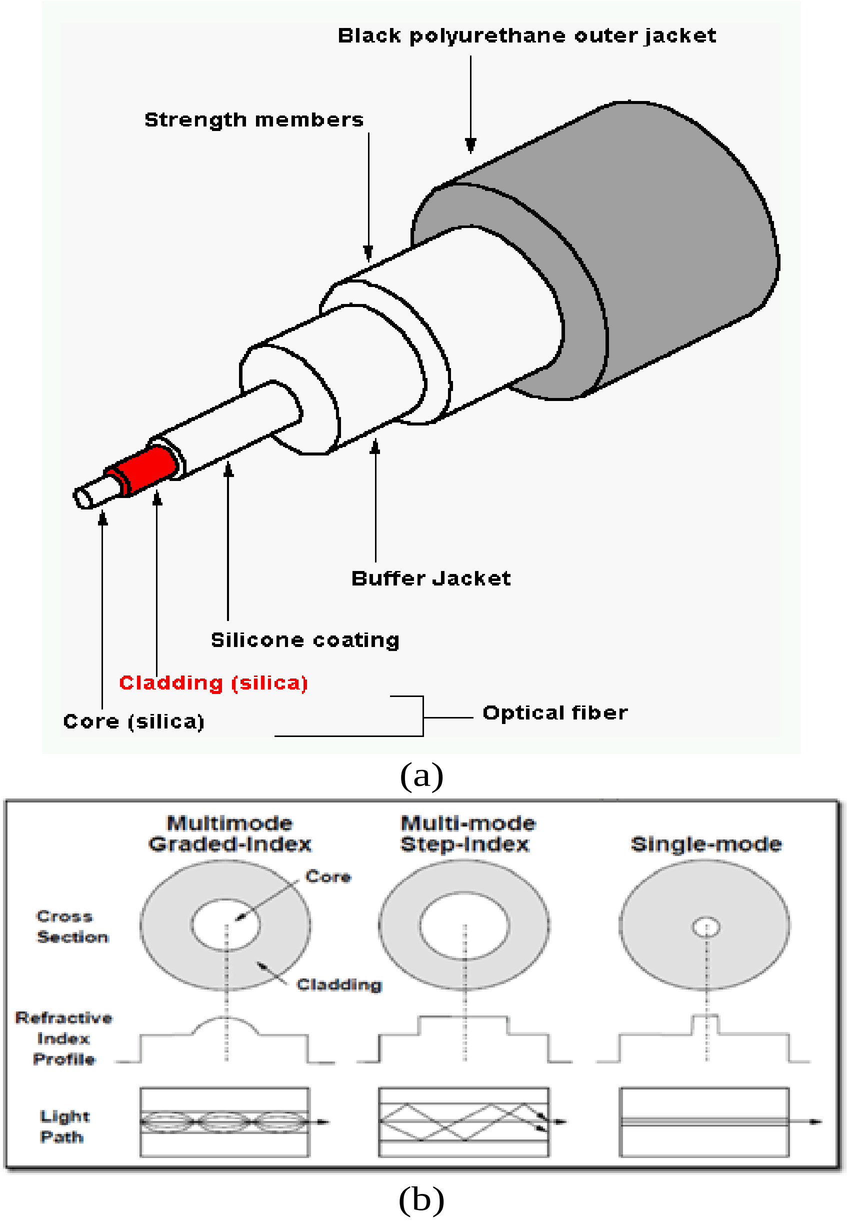

Fig. (2). (**a**) Structure of optical fiber [26, 27]; (**b**) Fiber dispersion and modal dispersion [26, 28, 29].

The components of an optical fiber are shown in Fig. (**2a**). The optical fibers can be classified as:

[a] Single-mode and multimode, respectively, depending on their size.
[b] Step and gradient index fibers according to their refractive index profiles.
[c] Polymer optical fibers (POFs) and silica optical fibers (SOFs), according to their material.

The core of the fiber, which has a refractive index value, and is surrounded by the cladding, which has a higher refractive index, efficiently guides light into the core of the fiber. The core may support many propagation modes as the wavelength of the operation grows, and the fiber can split into single-mode and multi-mode fibers as a result.

Multimode fibers provide a substantially higher light capacity than single-mode fibers, and the light may be guided into the core more precisely. However, having several modes reduces the quality of the light beam that leaves the fiber. Because various modes have different light speeds, the light at the output spreads in the time domain, a process known as dispersion. The core's refractive index profile can be designed to drop gradually from the center to the edge, which will cause light to bend along its transmission path and reduce dispersion in multimode fibers. Gradient index fibers are the name given to these kinds of fibers (Fig. **2b**).

More cost-effective, environmentalally-friendly, and sustainable building materials are needed today. Given that concrete is the most widely used construction material in the world, this has spurred a great deal of study in the sector. From the series of research, some researchers have come up with translucent concrete, also known as light-transmitting concrete. This concrete has many potentials that make it a good material that solves the problems faced in construction. However, due to poor awareness, cost, and availability of materials, translucent concrete is still not well known in many parts of the world. Where it is known, the availability of the material and cost of the material that is the main component that transmits becomes a challenge. The current paper reviews and analyzes qualitatively, the properties of translucent concrete, the aggregates, the limitations, and the advantages. Recommendations on the possible way by which the strength and durability of translucent concrete, especially when exposed to harsh environments, can be improved. Although other types of light-transmitting materials are only briefly mentioned or covered in this study, this is done to let the readers know that translucent concrete can also be made from other light-transmitting materials. However, because of its unique qualities that set it apart from other materials, optic fiber received a lot of attention in this study. It is the most popular light-transmitting material identified by numerous researchers, and these characteristics are discussed further in this study. The review study on translucent concrete revealed a good deal of limitations and research gaps. Some of the unmet needs include strengthening translucent concrete, determining the optical fiber percentage that will produce a durable concrete mix, and determining the impact of varying optical fiber ratios on the material's strength and energy-saving qualities.

2. AGGREGATES FOR TRANSLUCENT CONCRETE

Transparent concrete's light-transmitting materials are important for light transmittances and prices. The use of POF in daylighting systems has significant potential due to its high transmittance and low cost.

Water, fine aggregate, cement, and roughly 2% to 6% of the volume of the complete sample of optical fiber make up cement-based transparent concrete. The strength, serviceability, and durability criteria must be met for load-bearing and non-bearing transparent concrete panels or facades to handle anticipated ultimate loads with allowable deflection [21]. Additionally, the light transmittance performance must fulfill requirements like the Australian/New Zealand Standard [30] and the minimum illuminance level for human ocular activities in indoor contexts.

According to a study [31], it is practical to omit coarse aggregates from a combination used to create “light-transmitting cement mortar” to achieve higher homogeneity and compaction, which improves TC's light transmission. On the other side, there are worries about overlooking the optical fiber alignment since concrete vibrates. Self-compacting concrete is the greatest option for TC manufacture with good homogeneity to solve this issue. Consequently, much attention is paid to the freshness and hardening properties of self-compacting concrete to make it cleaner and more sustainable, either by replacing fine aggregates with industrial by-products or by adding steel or polymeric fibers [32, 33].

According to the study by Shanmugavadivu *et al*. [34], the following mix proportions were utilized to create transparent concrete blocks: 360 kg/m^3 of cement, 560 kg/m^3 of sand, 4.5 kg/m^3 of fiber, and 190 L/m^3 of water.

Nano-optic fibers and fine concrete are the two main ingredients of transparent concrete. Cement, aggregate, and water form the foundation of the substance, matching the fundamentals of concrete [35]. The binder that sets and hardens over a specific time and gives the product shape is cement, typically Portland cement. The material is strengthened by coarse aggregates like crushed granite or hard basalt fragments. Coarse particles are often absent from translucent concrete because they harm the fibers and prevent light from passing through the concrete block [36]. Despite being chemically inert, fine aggregates have an impact on the material's strength by filling in the gaps and lowering porosity. Sand is a typical fine aggregate.

All acids, alkalis, oils, and other organic contaminants must be absent from the water utilized. Craft clay is further used as a substrate for the optical fibers to combine with the concrete in addition to the desired fast-setting cement for the mixture. Additionally included are superplasticizers like Neoplast, Glenium, Polyplast SP HPC, etc. To boost refractivity, the substance is mixed with crushed, hammered, and ground industrial waste glass [37].

3. TRANSLUCENT MATERIALS FOR THE PRODUCTION OF TRANSLUCENT CONCRETE

3.1. Optical Fibers

A thin, flexible, transparent fiber known as an optic fiber (Fig. **3**) serves as a waveguide or “light pipe” to carry light between its two ends. The optics can range in size from 200µ to 1 mm [38].

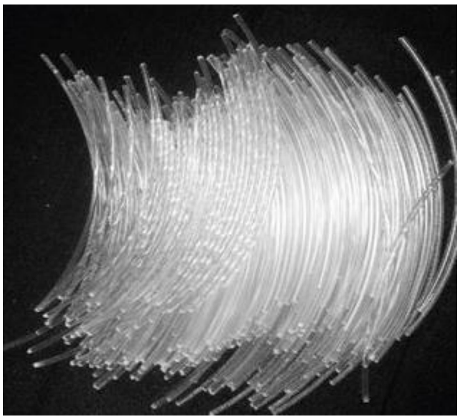

Fig. (3). Typical plastic optical fiber [12].

The speed of light inside a certain material is indicated by the term “refractive index,” which is a crucial parameter in optics [39].

The ratio of the speed of light in a vacuum to that in a second medium with a higher density is used to calculate the refractive index (also known as the index of refraction) [40]. An optical medium's refractive index, which is a dimensionless number in optics, indicates how well the medium bends light. When light enters a material, this determines how much of the light's path is bent or refracted [41].

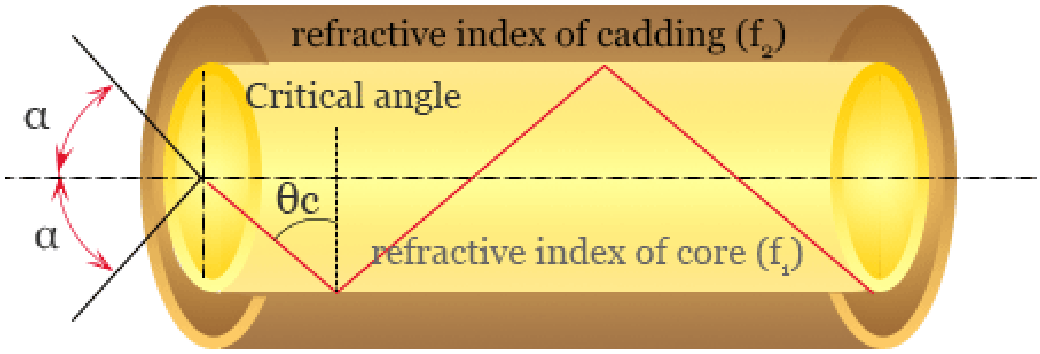

Fig. (4). Systematical representation of a typical fiber [43].

The properties of optical fiber are listed below.

[i] Coaxial shielding material with a higher refractive index surrounds the core of an optical fiber before a buffer-protective coating is applied to the outside. Within this coaxial core tube, the transmitted light moves through internal reflection [42].
[ii] Light-emitting in varying colors
[iii] Brittle, which is why such fibers are encased in steel wire
[iv] Washable

A typical fiber is systematically represented in Fig. (**4**).

The sine of the maximum angle of light entering is the numerical aperture (NA) of a fiber. Eq. (**1**) is a mathematical representation of it.

$$NA = f_{ext} b \sin\alpha = \sqrt{(f_1^2 - f_2^2)} \qquad \textbf{(1)}$$

where f_{ext} is the external medium's refractive index, f_1 is the coaxial core tube's refractive index, and f_2 is the cladding's refractive index.

Various fibers have various NA values. Higher NA values correspond to higher core values for cladding. However, a larger dopant concentration results in more scattering loss as NA increases.

Equally significant is attenuation, which is the loss of light per unit length at various wavelengths. It is known as attenuation and is measured in decibels per kilometer. Eq. (**2**) mathematically expresses attenuation.

$$db = 10 \log P_0 / P \qquad \textbf{(2)}$$

where P_0 is the input intensity, and P is the fiber's output intensity.

3.2. Plexiglass Material

High levels of transparency and the capacity to transmit light and color in both straight and curved lines without compromising transparency are both provided by plexiglass materials. Additionally, it is a suitable material for manufacturing translucent concrete due to its low cost and availability [43].

3.3. Other Possible Materials

A new kind of translucent concrete was created in 2010 by mixing glass with concrete in varying amounts to focus more on transparency so that it may be utilized in green buildings [44] and some properties of glass in structure have been studied [45].

According to the study [46], a remedy for these flaws was the addition of transparent plastic bars with a diameter of 5mm and 10mm along with polyvinyl alcohol. This helped to allow light to pass through the concrete and prevented the bonding between concrete and plastic bars, arrested cracking, and increased ductility. The findings demonstrated that the plastic bars' insertion decreased the concrete matrix-fiber transmission ability [46].

Additional fiber types that are employed include multimode, single-mode, multimode step-index, multimode graded-index, and others [37]. Light-transmitting concrete (LTC) can be made using waste tempered glass (WTG) as the aggregate [47].

4. PRODUCTION OF TRANSLUCENT CONCRETE

Due to optical elements—typically optical fibers—incorporated in the concrete, translucent concrete can transmit light. The stone allows light to pass through it from end to end. As a result, the fibers penetrate the entire object. Depending on the fiber structure, this causes a specific light pattern to appear on the adjacent surface. Through the material, silhouettes of shadows cast onto one side can be seen [48].

The method of production of translucent concrete is the same as that used to produce traditional concrete and some other varieties [49]. The only difference is the inclusion of optical fibers in the translucent concrete placed in the mold, spaced 2 to 5 mm apart and parallel to one another. The fibers are infused with the concrete as it is poured in thin layers over one another. Smaller layers allow an increased amount of light to pass through concrete. Translucent concrete, which can transmit both artificial and natural light, is made using thousands of fiber strands. Since coarse aggregate tends to damage fiber strands and reduce the concrete block's ability to transmit light, it is not used in production [50].

In addition, the procedures for producing translucent concrete are briefly described in 6 (six) steps as written in the research [37, 51], as well as the steps shown in Fig. (**5**).

The steps for the production of translucent concrete outlined in Fig. (**5**) are explained below and demonstrated in Fig. (**6**).

4.1. Step 1 is the Preparation of the Mold

A wooden or steel mold is produced based on standard dimensions. The clay or mud is placed on the sides where the optical fibers are exposed to the mold for easy demolding after the concreting (see Fig. **6a**).

4.1. Step 2 is the Preparation of the Optical Fiber

The optical fibers are cut carefully to the required size of the mold. The commonly available diameters of optical fibers are 0.25 mm, 0.5 mm, 0.75 mm, 1 mm, and 2 mm (see Fig. **6b**).

4.3. Step 3 is Fixing the Fibers in the Mold

Fibers are placed either in organic distribution or in layered distribution. Holes are driven on the wooden or steel plates through which optical fibers are allowed to pass (see Fig. **6c**).

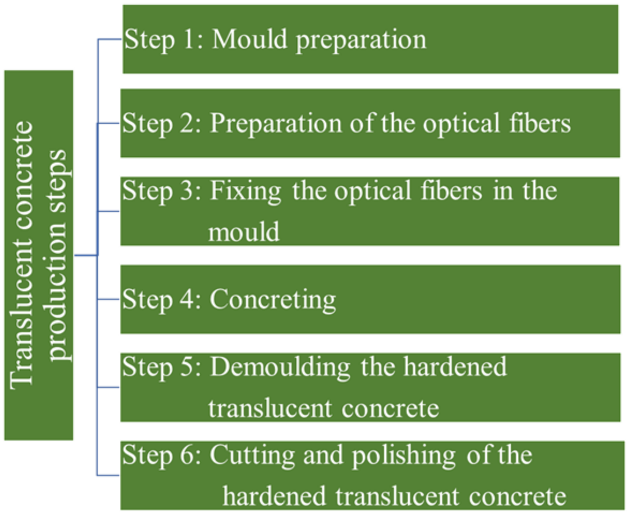

Fig. (5). Procedures for the production of translucent concrete.

Fig. (6). Steps for the production of translucent concrete: (**a**). Preparation of panel; (**b**). Optical Fibers; (**c**). Fixing of fibers; (**d**). Concreting; (**e**). Cutting and polishing of the surface [52, 53].

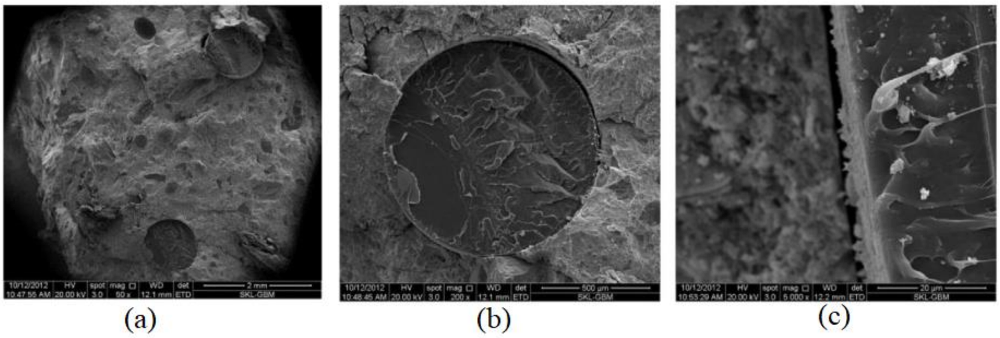

Fig. (7). SEM images of light transmitting cement-based material: (**a**) Matrix with optical fibers; (**b**) cross-section of optical fibers; (**c**) fiber/matrix interface [18].

4.4. Step 4 is the Concreting

The thoroughly mixed concrete is poured carefully and slowly without causing much disturbance to the previously laid optical fibers. The concrete is filled in smaller or thinner layers and is agitated with the help of vibrating tables to avoid void formation (see Fig. **6d**).

4.5. Step 5 is De-molding the Hardened Concrete

After 24 hours, the mold is removed, and the mud is pulled off. The casted mold was kept undisturbed on the leveled platform. Then, it was de-molded carefully after 24 hours from casting. Immediately after de-molding, the cube specimens were marked by their respective identification marks/numbers (ID).

4.6. Step 6 is Cutting and Polishing

The extra-long fibers are cut the same as the thickness of the panel. The panel surface is polished by using polishing paper or using sandpaper (see Fig. **6e**).

5. PROPERTIES OF TRANSLUCENT CONCRETE

Through a series of experiments, the study [54] attempted to determine the strength and durability properties of translucent concrete by using a water permeability test. It was discovered that transparent concrete with 4% optical fiber is more durable than conventional concrete and more durable than transparent concrete with 2.5% plastic optical fiber by 28% [54].

5.1. Mechanical and Physical Properties

From the studies conducted by many researchers [55 - 58], it was identified that the quantity or percentages of optical fibers added to the concrete have an impact on the mechanical properties of the translucent concrete. In their studies, it was discovered that an increase in the percentage of optical fibers caused a decrease in the mechanical properties of the concrete. Whether translucent concrete could be used for the development of green buildings was of concern, so it necessitated compressive strength (f_c) comparison between translucent and conventional concrete in the research [59]. To prepare the translucent concrete, optical fibers made of fibers were mixed with concrete.

According to Altlomate *et al*. [17], the maximum f_c at 28 days was 34.16 MPa with 1.5 mm POF diameter at 10 mm spacing. This indicates that the addition of POF to concrete enhances its f_c and that the f_c of transparent concrete also rises with time. They began to research and speculate about the qualities of POF since they were unable to get any information about it from the manufacturer. Following suit, Henriques *et al*. [60, 61] investigated the mechanical characteristics of light-transmitting cement-based material (LTCM) containing POF, first in an organized manner in the first research and then randomly in the other research. They concluded that raising the POF concentration in their tested specimens caused the f_c and flexural strength (f_f) to drop. They also showed that adding 5% POF randomly made the mechanical qualities of LTCM decrease than when POF was in order. Still, LTCM was nonetheless appropriate for use in construction in both scenarios. Studies [60 - 62] have shown how crucial it is to utilize silica fume as a partial replacement of cement in transparent concrete to prevent microcracks caused by the proximity of POF in translucent concrete specimens. Previous research [18, 19, 63, 64] came to the same conclusion that the f_c and f_f of LTCM decreased as the volumetric ratio of the optical fiber increased. The excessive smoothness of the optical fiber surface, which weakened the link between them as seen in the Scanning Electron Microscopic (SEM) test (see Fig. **7**), was blamed for the gaps in the fiber-matrix interface [18, 19, 60, 61, 63, 64].

Furthermore, Salih *et al*. [20, 65] reported a comparable finding that, despite a drop in f_c and f_f When the combined POF content rose, the f_c and f_f improved with aging. They also suggested that by increasing POF sizes and proportions, lightweight boards may be made due to a decrease in the density of their transparent concrete. To create their translucent concrete, the authors used various POF volumetric ratios (2%, 3%, and 4%), as well as various POF diameters (1.5, 2, and 3 mm), in a self-compacting mortar (SCM). This concrete reached a f_c ranging from 31.1 MPa to 40.4 MPa as well as f_f from 5.89 MPa to 8.12 MPa on day 28. Similar results were obtained by Tuaum *et al*. [12], who included (2%, 4%, and 6%) POF volume ratios of (2 and 3 mm), POF diameter into SCM and concluded that the density, the f_c, and the f_f decreased as the POF volume ratios increased. Although the f_c of transparent concrete specimens is lower than that of the reference specimens, it became better as the POF ratios were increased and as the curing time increased. However, Bashbash *et al*.

[66] discovered that by increasing f_c thereby increasing the POF diameter, transparent concrete could be produced using the same POF volumetric ratios (2%, 4%, and 6%) of POF diameters (1.5, 2, 2.5, and 3 mm) in a mortar. Despite the evidence showing that f_c and f_f dropped as the POF quantity increased. This is because the higher-diameter POF is more rigid and has greater compressive load resistance than the lower-diameter POF.

The relationship between the POF volume percent and the quantity of transparent concrete was established; the greater the POF volume fraction, the lower the f_f of translucent concrete [67 - 69]. While Momin *et al*. [70] concluded that transparent concrete mixed with glass optical fibers proved the same f_c as conventional concrete, it was less effective than translucent concrete combined with glass rods because the glass optical fiber was less rigid than the glass rods.

In the study [55], concrete specimens were made by adding glass rods and optical fibers in various percentages and comparing them to conventional concrete. Light transmission and compressive testing are conducted in addition to cost comparisons in these two tests. From the analysis, the compressive strength of the concrete with glass rods and optical fibers was lower than that of the conventional concrete, while the compressive strength of glass rod concrete was lower than that of optical fiber concrete.

He, Zhou, and Ou [68] concluded that the larger the volume ratio of POF, the lower the f_c of the translucent concrete observed. So, endlessly increasing the transmittance by way of increasing the POF volume ratio is not possible, as it would have a detrimental effect on the casted cube's mechanical properties.

In contrast to a failure load of 201.8 kN for a normally cast concrete block of the same size, Zhou *et al*. [23] observed that the failure loads for concrete blocks with 3.14%, 3.80%, and 4.52% of POF by volume were 201.0 kN, 195.7 kN, and 182.2 kN, respectively. This resulted in a decrease of 0.379%, 3.023%, and 9.712% for the concrete blocks with comparable POF volumes of 3.14%, 3.80%, and 4.52%.

According to a study [71], conventional concrete can achieve a maximum compressive strength of 22 to 30 N/mm^2 for a M20 mix design. Comparing optical fiber-containing concrete to regular concrete, the latter exhibits a decrease in compressive strength. The optical fibers that have been added, which barely make contact with the cement paste, are to blame for this. Additionally, in their study, transparent concrete cylinders measuring 100*300 mm were tested for tensile strength using a universal testing machine. When translucent concrete specimens are contrasted with conventional concrete, stress *vs*. strain depicts the uniform elastic deformation. When they used an optical fiber with a 2mm diameter, the highest tensile strength they could achieve was 7 N/mm^2. Contrarily, in conventional concrete, sudden failure of the material can be observed, and the highest strain reached is 3.14 N/mm^2 [71].

5.2. Stress-strain Behavior for Translucent Concrete

The slope of the stress–strain curve for concrete under uniaxial loading determines the static modulus of elasticity under tension or compression. The elastic property of a material is a gauge of its stiffness, but this curve for concrete is nonlinear [72]. As a result, stronger concrete has a more elastic static modulus [73]. A crucial factor expressing concrete's ability to deform elastically is its modulus of elasticity. The modulus of elasticity is important because, for a given strain, a higher modulus produces a higher tensile stress, which means that stronger concrete exhibits a lower strain. As a result, the length of the member under compression affects the descending branch of the stress-strain relationship [74].

In comparison to concrete boards without optic fiber, the study [75] looked at the stress-strain behavior of translucent concrete boards of various dimensions. Figs. (**8**, **9**, and **10**) show the stress-strain diagram for all types of boards. Based on these data, it can be concluded that the embedding of POF in the mortar causes a reduction in the static modulus of elasticity in translucent concrete for all types of boards because the POF has a low modulus of elasticity that is less than 2.1*10-2 GPa [76]. Following [72, 77], the POF causes the mortar to become more porous, which causes the modulus of elasticity to decrease.

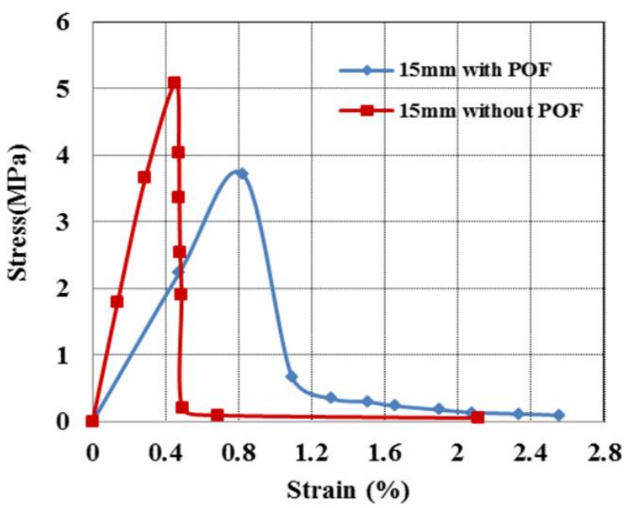

Fig. (8). Stress-strain behavior for the translucent concrete board of 15 mm height [75].

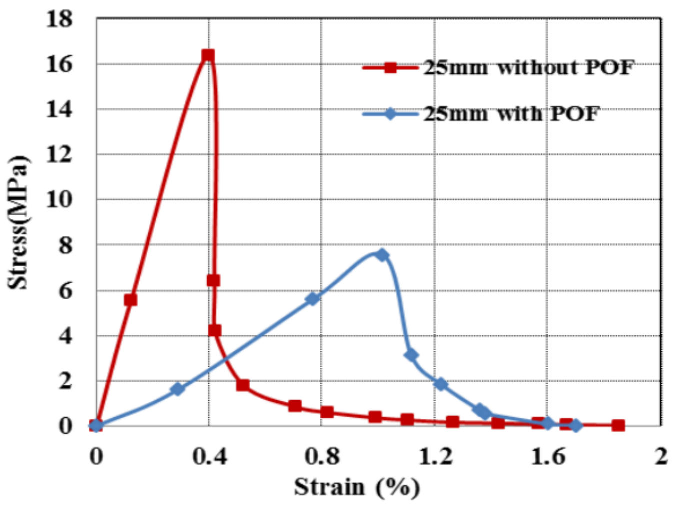

Fig. (9). Stress-strain behavior for the translucent concrete board of 25 mm height [75].

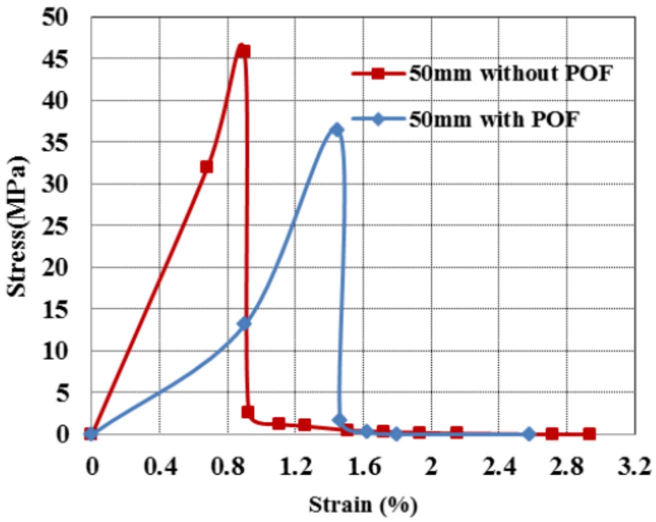

Fig. (10). Stress-strain behavior for the translucent concrete board of 50 mm height [75].

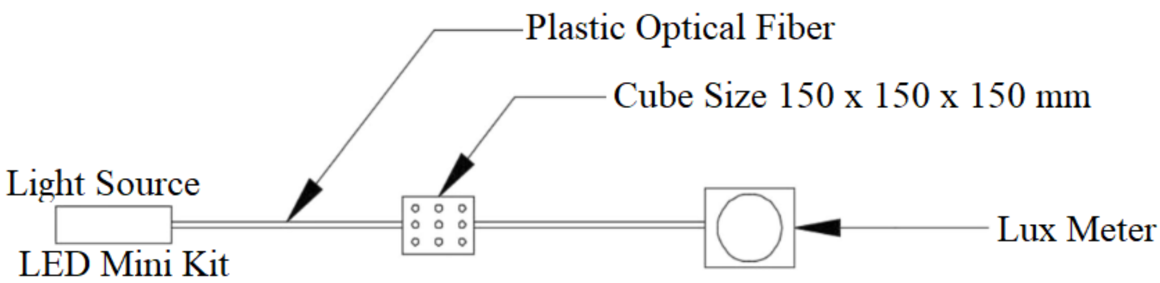

Fig. (11). Schematic diagram of the setup of light transmittance test [78].

5.3. Light-Transmitting Property

The compressive behavior and light transmission capabilities of transparent concrete were studied [32]. The f_c was found to rise by 3% with the addition of fibers to the concrete volume (0.10%–0.20%), and the highest quantity of light that could travel through the cube was 2122 lux.

The effectiveness of Light Transmissive Concrete (LTC) specimens produced utilizing various dosages and spacings of POF was examined by Altlomate *et al*. [17]. The effectiveness of POF was examined and evaluated.

Momin *et al*. [70] built a lux meter to gauge the amount of light that was able to penetrate through the concrete blocks. The amount of light passing through was measured using a Light Dependent Resistor.

In the study [78], which examined the light transmittance characteristics of translucent concrete, the amount of light was measured in lumens with a lux meter, with a range of 0.1 to 100,000 lux. The light source was a 16W LED fiber mini optic mini kit. To prevent losses, the concrete cube specimens were stored in a wooden box that measured 2 feet by 2 feet. The lux meter readings were recorded. The experimental setup for the test of light transmittance is shown in Fig. (**11**). Using insulation tape, the optical fibers from the concrete specimens are tightly rolled and placed on both sides of the concrete specimens. One side of the fibers is connected to the intensity of the LED mini kit light source, and the other side is connected to the Lux meter. The light intensity can be determined through this illuminance test.

The amount of light transmitted through transparent concrete was determined by Li *et al*. [19] using 3-6% optical fiber. The results of the spectrometer test led him to the conclusion that by increasing the number of optical fibers in this material, the amount of light flowing would be greatly increased. After that, Kim *et al*. [79] developed weightless transparent concrete by substituting plastic rods for optical fibers. The findings of this study showed that light transmittance is inversely related to pipe length. In this study, rod flexibility was significantly lower than that of polymethyl-methacrylate (PMMA) optical fibers. A unique light-transmitting cementitious composite (LTCC) was created in another study by switching out microencapsulated phase change material (MPCM) to reduce the amount of energy that buildings use to transfer light through the concrete [80].

Utilizing Autodesk Ecotect Analysis software, several simulations on the measurement of light-transmitting concrete were conducted [7, 81, 82]. It was discovered that utilizing light-transmitting concrete may boost the brightness of the room by up to 30% because more light penetrates the space.

5.4. Temperature Effect, Thermal and Energy-saving Properties

By harnessing sunshine and reducing the need for artificial lighting throughout the night, using light-transmitting concrete will provide a decorative aspect. After examination, transparent glazing solutions have demonstrated excellent thermal insulation characteristics [83, 84]. On the other hand, a transparent concrete panel (TCP) achieves the same thermal performance by utilizing concrete components and additives that are energy efficient.

Huynh *et al*. [85] described the effect of temperature, light source distance, and fiber diameter on the light transmittance of LTC [86]. According to the researchers [85], arranging optical fibers with high content in the light-transmitting concrete (LTC) helps to enhance the light transmission ability of this material.

The lighting efficiency of both commercial and residential constructions may be significantly improved by transparent concrete, which can transmit up to 12.4% artificial light and save up to 14% of energy when compared to conventional windows [80].

According to testing results in [7], the OF and unsaturated polyester resin had the same rates of light transmission. The latter is chosen since it is less expensive to build. Therefore, it is straightforward to implement TCP with large-diameter light conduits by employing different diameters of plastic pipes as the molds for the light conduits. When compared to a plain façade, the numerical simulation revealed that the resin TCP façade's energy efficiency was promising [87]. A resin light conduit with a rectangular cross-section was placed within the TCP [25]. A computer model was created to analyze the light transmittance performance of the TCP for the building façade. To provide adequate light transmission performance and f_c, Rosso and Melo [88] created a TCP that included recycled glasses. These glasses were employed to substitute mineral aggregates ranging from 20–61% with an ideal percentage of 46.2%. Compared to OFs, the TCP was substantially less expensive. Using strontium aluminate, a glow-in-the-dark material, Saleem and Blaisi [89] created TCP blocks.

A volumetric fiber ratio of 6% used in the TC panel, according to preliminary research results [22], results in a 50% reduction in lighting energy use. If panels can lower the office space's need for heating and cooling, their utility is increased. When sunlight is transmitted through optical fibers, it can help heat a room in the winter but increase cooling loads in the summer. Additionally, daylight has a positive impact on cooling loads and heat loss from lighting installations. In the morning, heat can be removed from the room through conduction through the walls, but in the late afternoon and evening, heat from the surrounding environment can be transmitted into the room. An ideal fiber volumetric ratio for TC panels that would save energy is sought after by the research that combines thermal and lighting analyses. For a fiber volumetric ratio of 5.6%, the TC panels can reduce energy consumption by 18%, making the fabrication process feasible.

A novel building envelope material was investigated in the study [87] using polymethyl methacrylate resin embedded in concrete, which can offer excellent natural light illumination and an excellent combination of shielding performance and clarity. By using the flat plate method and optical power method, respectively, the thermal conductivity and light transmission of resin translucent cement-based material (RTCM) were measured. The Autodesk Ecotect Analysis 2011 software was used to conduct an energy and daylighting simulation to assess the building's energy usage and daylight level. The lighting uniformity improved by almost 50%, and the natural lighting coefficient increased by almost 100%. The artificial lighting system's operating time was cut in half, from 72% to 41%. Additionally, it is possible to reduce the cooling/heating load by nearly 20% under the current test conditions. The outcomes demonstrated the superior thermal conductivity and light transmittance of RTCM. The indoor lighting and visual comfort could be effectively improved by RTCM.

An experimental study on a translucent concrete panel investigated the light emissions and thermal properties by modeling the arrangement of the optical fibers into the concrete during exposure to simulated sunlight for 12 months. Results proved the good thermal and mechanical properties of translucent concrete [68].

Computing modeling for a transparent concrete panel with dimensions (0.3 m*0.3 m*0.1 m) was made [90] using a fiber volumetric ratio of 10.56% to investigate the model's light transmission properties under the weather in Berkeley, California. Throughout a year of simulation, an algorithm is utilized to model and compute the transparent concrete panel's solar heat absorption. The results of this study will create a formula for calculating the amount of sunshine that will enter a building when transparent concrete is employed. This will have an impact on following design decisions made during the heating, ventilation, and air conditioning (HVAC) design process. To provide thermal and lighting evaluations [22] and estimate the ideal optical fiber ratio for transparent concrete panels to conserve the most energy feasible, new research was carried out as a follow-up to the prior work [90]. The investigation will make use of a model room with the dimensions (3 m*3 m*2.895 m), and panels with the same measurements as the computational model from the earlier research will be produced in the lab. The program was developed to simulate and calculate the heating and cooling loads on the HVAC system, as well as other light and thermal assessments, to find the optimal ratio of optical fibers for panels that would achieve the most potential for energy savings. According to this, employing fiber with a volumetric ratio of roughly 6% results in an 18% decrease in energy use.

6. APPLICATIONS

Since light transmission and transparent concrete may disclose the shadows of any surrounding objects put on the brighter side of the wall, they can be used in the building of jails, banks, and museums to provide safety, monitoring, and security [91]. However, there could be some limitations to the use of translucent concrete in places like banks and museums. This limitation ranges from the high cost of using optic fibers in the concrete, which makes translucent concrete expensive, to the manpower in this area of construction. The poor strength recorded by some researchers when the optical fiber is incorporated into concrete could be a thing of concern for this type of concrete to be used in security-sensitive areas like banks and museums. Residential and commercial buildings consume the most energy for electric lighting. The building industry is responsible for 34% of the world's energy use [92]. Around 19% of the total provided power worldwide is used for artificial lighting [93]. The need for electric lighting has been growing significantly because of population increase, urbanization, and the construction of towering structures. Natural sunlight is impeded from passing through when high-rise buildings are constructed close to one another because of the neighboring structures' obstructions. Buildings' indoor environments are always kept bright throughout the daylight thanks completely to artificial light, which uses a lot of electricity. Utilizing natural light indoors decreases the demand for artificial lighting, lowers energy costs, and improves occupant comfort levels. It has been demonstrated that indoor spaces with sufficient natural light lighting reduce stress on occupants, enhance visual comfort, and result in higher staff retention [94].

Although transparent concrete isn't used much today, some potential uses are being considered for implementation [50]:

[i] Illumination of interior building spaces. Buildings and basements have long been associated with drab and depressing concrete. Transparent concrete has the potential to alter the stereotypical perception of concrete by allowing light to pass through it, changing the interior of buildings so they appear more light-filled, airy, and spacious.

[ii] The people inside can see when someone is standing outside, thanks to the translucent concrete used for front doors in homes and offices.

[iii] Translucent concrete can be used as flooring on a surface illuminated from below. It appears like typical concrete pavement during the day, but at dusk, the paving blocks start to shine and change color.

[iv] Sidewalks may be constructed by using transparent concrete and with lighting underneath, creating a passable surface that would employ more safety for pedestrians during the night, which is at a very high risk.

[v] Transparent concrete can also be used as interior walls, facades, and dividing walls based on panels.

[vi] Creativity with the designing, logos and other aesthetic structures can also be made using transparent concrete. It takes an artsy mind to design these structures. It can also be used to design floors and furniture.

[vii] Subways, which are sometimes too dark, can also be illuminated. A stylish reception desk can also be made using it.

The usage of LTC in the construction sector has increased during the previous five years. Fig. (**12**) displays instances of LTC applications in different buildings from across the world. The Al-Aziz Mosque in Abu Dhabi is another example of a newly constructed edifice that uses LTC technology. When the mosque was opened in 2015, optical fibers were used to change the illumination. LTC panels with a total surface area of 525 m^2 and dimensions of 1.8 x 1.4 x 0.3 m were used [95]. Another building built using the LTC approach was the Italian Pavilion at the 2010 Shanghai World Expo in China. Instead of using optical fibers in this LTC, a precast concrete panel was covered by the addition of specialized plastic resins (polymer-based material) to a creative mortar. 3774 LTC panels were used to cover 1,887 m^2 or over 40% of the building's envelope. Each plate is 1 x 0.5 m, weighs 50 kg, and is 5 cm thick [96].

In elegant architecture, translucent concrete is used as a façade material and for interior wall cladding. Several design products have also been made from translucent concrete [97].

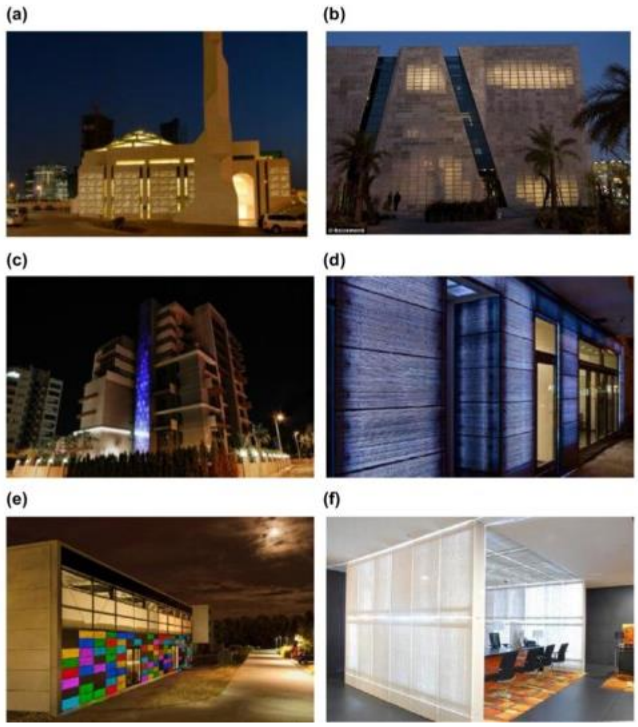

Fig. (12). Examples of applications of light-transmitting concrete: (**a**) Abu Dhabi, United Emirates, completed in 2015, 30 mm and 40 mm thickness, 525 m^2, (**b**) Shanghai, China, completed in 2010, 1887 m^2, (**c**) Izmir, Turkey, completed in 2015, 20 mm thickness, 300 m^2, (**d**) Berlin, Germany, completed in 2014, 20 mm thickness, 60 m^2, (**e**) Tbilisi, Georgia, completed in 2011, 15 mm thickness, 300 m^2, (**f**) Aachen, Germany, completed in 2012, 102 m^2 [17, 95, 96].

7. ADVANTAGES AND DISADVANTAGES OF TRANSLUCENT CONCRETE

7.1. Disadvantages

Some academics choose to research transparent cement mortar since compacting concrete in the presence of optical fibers can be challenging. Transparent cement mortar was shown in [57, 58, 98] to be more effective than transparent concrete.

Lack of experience is another factor keeping transparent concrete from totally replacing conventional concrete. Although professional work is needed to include optical fibers in the concrete mixture, few individuals are familiar with this technology [35].

Due to the usage of optical fibers, this concrete is more expensive to produce than regular concrete since it is translucent.

The labor-intensive process of casting translucent concrete blocks necessitates the use of specialists with specialized knowledge, increasing the cost of production once more. For the following main reasons, *i.e*., LTC is still not widely used as a novel building material because of the high cost of glass optical fiber and the difficulty of installing fiber.

There are other factors, such as a lack of reliable advanced investigational information on durability and mechanical attributes to be examined for its entire service life period, that can prevent LTC from being applied universally in the infrastructure and construction industries, in addition to the aforementioned major drawbacks. Along with that, the design of such LTC also needs to be improved.

7.2. Advantages

The applications of translucent concrete are quite amazing to the eye since natural sunlight is the best free-of-cost source of light. The bright illumination is possible to produce in a room constructed with translucent concrete walls using free natural sunlight. The optical fibers also function as heat insulators, and hence, they are very effective in countries with cold weather. Translucent concrete application in constructing buildings saves energy consumption because it is eco-friendly owing to its light-transmitting attribute. Thus, it is obvious that translucent concrete is a great potential tool that is competent enough to save electricity and cost as well.

Translucent concrete is continuously being researched and developed. However, there are other benefits to this kind of concrete that may be stated [15, 24, 67, 99]:

- By allowing a solid wall to transmit light, less lighting will be required within the home during daytime hours, resulting in energy savings.
- Its architectural benefit is that it provides an excellent aesthetic view of the building.
- When light cannot be effectively permitted to a confined area, transparent concrete may be employed.

8. DISCUSSION

With the growing need for green buildings and alternative building materials, translucent concrete has a bright future. Because sunlight can easily pass through translucent concrete to provide visual clarity for the occupants even at night when the moon is out, translucent concrete is environmentally friendly, sustainable, and less expensive for the government and individuals to use during the day. Translucent concrete is a great way to save money and energy. Translucent concrete serves as a superior replacement since it is approximately as robust as conventional concrete blocks and stronger than glass [99].

Apart from the results from the research by Altlomate *et al*. [17], the majority of investigations generally showed that the addition of POF reduced the strengths of transparent concrete. However, most of them agreed that lengthening the curing time increases compressive strength. Among these experiments, Halbiniak and Sroka [100] looked at the impact of compressive stresses applied parallel or perpendicular to the POF orientation on transparent concrete specimens. They verified that when the parallel and perpendicular loading orientations were on the POF orientation, respectively, the loss in compressive strength of the transparent concrete relative to the reference concrete (without POF) was 38% and 19% [100]. As a result, most of the research concluded that the POF configuration with perpendicular loading is preferred. Numerous industry experts have projected that transparent concrete will revolutionize the market as a whole and replace regular concrete as an affordable and environmentally friendly material.

To make translucent concrete an accessible solution for both commercial and residential buildings, producers are currently putting a lot of effort into developing transparent concrete at a reduced cost [95]. LTC offers excellent qualities but is high priced because it requires pricey optical fibers and has limited widespread commercial implementation [19]. So, to make judgments that are cost-effective, economic analysis is essential. According to a review of the literature, there is a paucity of investigation of the quantity of optical fibers and the amount of light passing through concrete walls with different percentages of optical fibers [22]. The amount of electrical energy that will be conserved and the amount of light that will pass through various types of light-transmitting concrete in different places such as galleries, offices, or other space walls (with 3-15% optical fibers continent) are thus unknown. In a prior study, high-performance light-transmitting concrete samples with five optical fiber contents (3%, 5%, 7%, 10%, and 15%) were made by integrating innovative matrix materials to reach the cost-effective quantity [62]. Compared to earlier studies, concretes prepared for this study contained more optical fiber, and the best option was chosen. These percentages were chosen based on those that were utilized in other publications [18, 26, 62, 64, 66, 101, 102]. Additionally, it was thought that increasing them by 1.5 or 2 times would make the variations in the light flowing through them more noticeable and observable. Additionally, it was not possible to produce concrete that contained more than 15% fiber optics due to constraints, including the large number of optical fibers needed and the reduction in the distance between the fibers [62].

Glass windows have been serving as a source of light in the room. This type of lighting system has its material readily available and cheap. Translucent concrete has more strength than glass windows, which means it is often important to provide more protective methods in structures bearing glass windows because it could serve as easy access for criminals to access the building in certain regions. The cost of acquiring the materials to produce translucent concrete surpasses the cost of glass windows. From the earlier reviewed works, the reason for the poor use of translucent concrete is due to its high cost optical fiber is the main contributor to this high cost.

9. RECOMMENDATIONS

It is safe to conclude that researchers will need to discover affordable production methods for transparent concrete before it can be considered a viable substitute. Research into less costly light-transmitting materials is strongly advised.

It is necessary to improve the strength and durability of translucent concrete especially when exposed to harsh environments hence, this study suggests the use of fiberglass mesh (Fig. **13**) as external confinement of the concrete and incorporation of fibers in the translucent concrete mix to enhance the strength of the concrete.

Fig. (13). Concrete fiberglass mesh [103].

Composite masonry mesh is a fiberglass rod of circular cross-sections, which are perpendicular and firmly fixed to each other at the connection points. The cells in the grid are most often square, and the minimum size is 50x50 mm, but products with larger cells are also produced. Composite mesh is usually produced in the form of rolls or cards (sheets). The width of the grid can be up to 2 m, while the length can be any. The main task of the fiberglass mesh is to strengthen the walls of the building, providing resistance to various types of damage [104].

9.1. Properties and Characteristics of Fiberglass Mesh

[i] **Corrosion and chemical resistance.** Fiberglass, unlike metal, shows excellent resistance to oxidation and corrosion as a result of exposure to a humid microclimate, salts, or chemicals. Due to this, the durability of the concrete floor itself, reinforced with fiberglass mesh, increases.

[ii] **Strength.** During the research, it was determined that the breaking capacity of the composite mesh is 3 times higher and exceeds the metal mesh of a similar diameter in strength. Due to this, while maintaining the strength characteristics, the metal mesh can be replaced with a composite plastic mesh of a smaller diameter. (for example, Vr-1 Ø3 mm - KSP 50X50 2; Vr-1 Ø4 mm - KSP 50X50 2,)

[iii] **Low thermal conductivity.** The thermal conductivity of composite reinforcement is 0.46 W / m^2, which is approximately 100 times less than the thermal

conductivity of metal. Thus, the composite mesh can be used to prevent the formation of “cold bridges” inside the structure.

[iv] **Ease.** If metal and composite mesh of the same size are compared, then the composite mesh is 6 times lighter in weight than its metal counterpart, which greatly simplifies construction and installation work.

[v] **Durability**. Masonry mesh is an extremely wear-resistant material that does not lose its properties over time. According to research by British scientists, over 100 years, the strength reduction coefficient of composite reinforcement is 1.25, that is, the strength of the material is maintained at 79.6% of the original level.

[vi] Fiberglass masonry mesh is a dielectric, not magnetized

Since glass fiber enables light to travel through it, using fiberglass mesh will not prevent transparent concrete from transmitting light; instead, it will improve the material's mechanical and physical qualities [104].

9.2. Strengthening Translucent Concrete with Fibers

In general, concrete material deteriorates over time and at various scales. When concrete is loaded, short, discrete microcracks initially appear in a dispersed pattern. Large macroscopic cracks, also referred to as macro cracks, are created when numerous microscopic cracks combine. Because there are so many optic fibers used in translucent concrete, the point at which a crack first appears is very large. Cracks should be avoided when creating translucent concrete for practical applications because they weaken concrete in a variety of ways. Since microcracks are the primary culprit for larger cracks, reducing them at the microscale level is crucial [105]. If left unchecked, this could cause concrete to lose its strength completely. To overcome this issue in translucent concrete, this section suggests the incorporation of fibers into the concrete mix of translucent concrete. It is important to note that the fibers that should be included in the mic are fibers that can allow light to pass through them to a certain amount.

CONCLUSION

Using conventional light-transmitting concrete is a clever strategy to maximize the sun's energy and a way to save non-renewable energy. Translucent concrete is a cutting-edge construction material. Translucent concrete has strong light-guiding qualities, and the optical fiber volume-to-concrete ratio is proportional to transmission. Translucent concrete may be used as a lightweight structural material to illuminate interior construction areas in addition to its many aesthetic uses. To increase its potential, more study is required. Most of the thermal and energy-saving research focuses on experimental or modeling studies of the possibility of integrating optical fibers with concrete to bring sunlight into interior spaces and analyze their ratios in concrete. Tries to find the ideal ratios to reduce the demand for industrial lighting and heating loads to save the most energy possible. Numerous studies on the mechanical characteristics of transparent concrete have compared its characteristics to those of ordinary concrete, highlighting the compressive strength value as one of the most important characteristics of the substance. Most of the research, however, indicates that further study is necessary since the mechanical characteristics of transparent concrete's strength are still inferior to those of regular concrete. Some studies looked at how adding fibers to transparent concrete might affect the mechanical characteristics in relation to the fiber ratios. To increase the strength performance, several of these studies used experimental research to examine the impact of optical fiber ratios on concrete mixtures with diameters ranging from 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 10%, and 15%. As predicted, the results showed that compressive strength declined as the proportion of optical fibers increased and that the ideal proportion for mechanical qualities is less than 5% of fibers per volume of concrete. As previously noted, the ideal ratio of fibers in concrete volume is less than 5% for improved mechanical qualities and 6% and above for energy savings. A proper understanding of the right percentage of optic fiber to be included in the concrete is essential. The pattern of placing the fibers is of high importance. From the review study, the diameters of the optical fibers mostly used were 0.25 mm, 0.5 mm, 0.75 mm, 1 mm, and 2 mm. Therefore, there is a gap in the literature about the optimal optical fiber ratios for concrete to obtain optimum energy savings and higher mechanical properties. It was discovered that adding POF to concrete drastically reduced its flexural strength. (In general, the pattern shows that flexural strength decreases as the POF volume ratio rises.

LIST OF ABBREVIATIONS

UHPC	=	Ultra-high-performance Concrete
LTC	=	Light-transmitting Concrete
POFs	=	Polymer Optical Fibers
SOFs	=	Silica Optical Fibers
WTG	=	Waste Tempered Glass

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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