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Review

Light Transmitting Concrete: A Review

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Abstract: Recently, research attention has been drawn to the application of novel, unique, and innovative types of construction materials to fulfil diverse objectives associated with the ground-breaking concept of "Greener Architecture", in order to improve the overall economic value and quality of construction. Among these revolutionary structural building materials is light-transmitting concrete, also referred to as translucent or transparent concrete. This material is based on the concept of nano-optics, which allows exterior light to transmit through internal spaces in which light elements, namely optical fibres, are incorporated during the material's manufacture. The current review assesses earlier studies of translucent concrete, focusing on its applications, and the appropriate ratio and arrangement pattern of optical fibres. This study also investigated the light-transmitting, mechanical, thermal, and energy-saving properties of translucent concrete by analysing research conducted during the past decade. However, numerous material restrictions and research gaps were found in the earlier literature on this concrete. The principal restrictions relate to the material's low material strength and the identification of the optimum ratio of fibres. The main gaps identified among the reviewed research investigations relate to tests aiming to identify the influence of dissimilar ratios of optical fibres on the material's strength and energy-saving properties. In the current review, we also identify and recommend future areas of research, and provide suggestions to address the existing research gaps. Finally, we review the types of translucent materials, their properties, and their advantages and disadvantages, and provide illustrations and value-added applications. The aim is to promote translucent concrete as an attractive, promising, and innovative building material for the construction industry.

Keywords: light transmitting concrete (LTC) or translucent or transparent concrete (TC); optical fibres (OFs); strength; energy-saving; greener architecture; nano-optics

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1. Introduction

Concrete is a revolutionary composite structural material that has been used extensively since the ancient Romans began using it for construction purposes. It is one of the most durable building materials, resulting in a long service life. As a result, it is the most used human-made material globally. Numerous varieties of concrete exist [1–10], of which, light-transmitting concrete (LTC), or translucent or transparent concrete (TC), has drawn significant attention of concrete technologists and global researchers due to its significance, usefulness, and unique properties. Its ability to transmit light not only results in an improvement concerning visibility, but also reduces the light energy demand of buildings [1]. In this product, optical fibres act as channels to transmit light from one side of the surface to another. These optical fibres are spread uniformly through the concrete and are visible on both sides of the LTC block. They appear as shadowy outlines through the LTC, and patterns form on one side of the surface. Regarding the product's performance, the concrete is embedded with optical fibres in a matrix, while retaining its strength. The LTC concept was first invented and developed in 2001 by the Hungarian architect Aron Losonczi [11,12]. As the pioneer of LTC, Losonczi developed the first transparent concrete block, which was coined "LiTraCon". The LTC innovation aimed to transfer light through opaque and dull concrete, and minimise the amount of energy required for illumination. LTC was found to be highly useful in a broad range of applications, such as partition walls that permitted the penetration of sunshine into interior spaces, thus increasing the illumination level in internal environments [13]. Research has confirmed that LTC is not only able to transmit light, but also to reduce light energy utilisation by up to 50% [14], 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. A large number of translucent materials may be used to develop LTC. However, in general, optical fibres (OFs) derived from aggregates of waste glass and polymer resin are used. Materials that possess high translucency or higher light transmittance can be used for LTC production. The transmission of light by optical fibres is sufficiently bright and efficient that almost no light is lost by the fibres [15–18]. Thus, the invention of LTC is an excellent solution for transmitting light inside structures.

Consequently, the present manuscript aims to provide a comprehensive review of LTC produced using OFs, in addition to its present and potential value-added applications for structural buildings and infrastructure. Furthermore, a critical discussion of the advantages and disadvantages of LTC is presented to increase the understanding and knowledge regarding the latest research on LTC manufactured using OFs, and its latest applications in the field. The advantages and disadvantages of LTC are listed, and LTC properties are also thoroughly reviewed.

2. Functioning Principle

An optical fibre is divided into three main parts (Figure 1a):

1. The core, in which the majority of the light travels;
2. The surrounding cladding;
3. The coating, known as the jacket, which protects the fibre.

The optical fibres can be classified: (1) according to their dimensions, as single-mode and multimode; (2) according to their refractive index profiles, as step and gradient index fibres; and (3) according to their material, as polymer optical fibres (POFs) and silica optical fibres (SOFs). A significant parameter in optics is the refractive index, which expresses the speed of light inside a specific medium. For the efficient guiding of light into the core of the fibre, the core, which has a refractive index value n_c, is surrounded by the cladding, which has a higher refractive index n_{cl}. As the radius of the core increases with the wavelength of the operation, the core can support more than one propagation mode, and the fibre can be divided into single-mode and multimode fibres.

Compared to single-mode fibres, multimode fibres have a significantly greater light capacity, and the light can be more easily directed into the core. However, the existence of multiple modes has a negative impact on the quality of the light beam exiting the fibre. As various modes have different light speeds, the light at the output spreads in the time domain, an effect known as dispersion. To minimise the dispersion in multimode fibres, the refractive index profile of the core can be engineered to gradually decrease from the centre to the edge, resulting in the bending of light along its transmission path. These types of fibres are called gradient index fibres (Figure 1b).

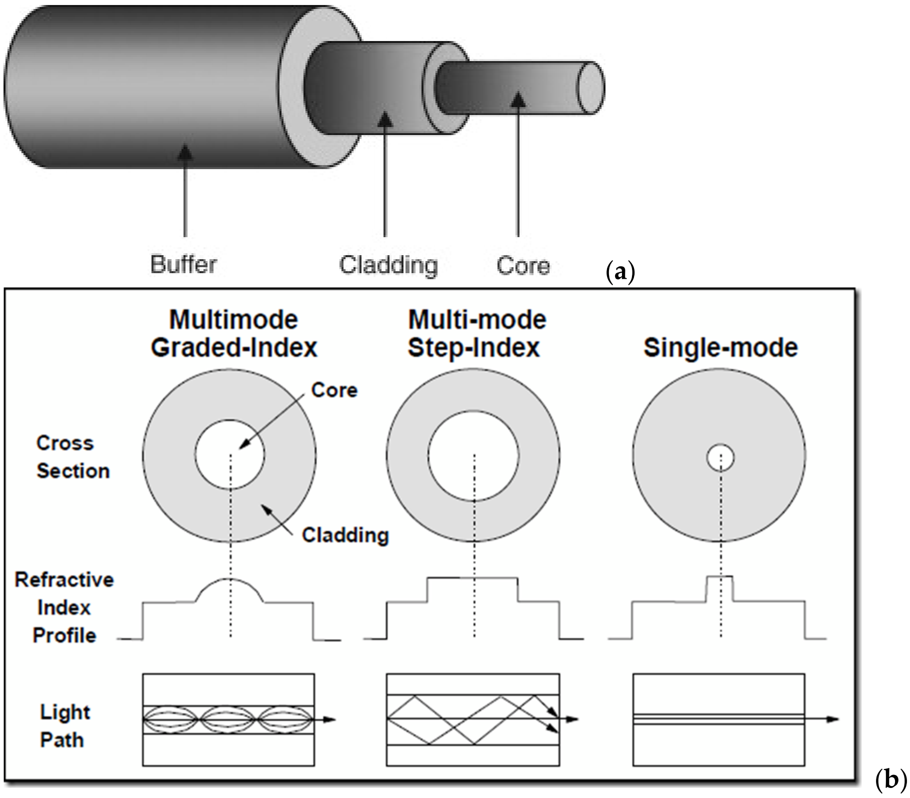


Figure 1. (**a**) Structure of optical fibre [19]. (**b**) Fibre dispersion and modal dispersion [20,21].

If one considers the light as a ray travelling through the fibre's core, then its transmission through an optical waveguide can be described through the Total Internal Reflection (TIR) phenomenon. The light launched into the fibre core with an incident angle (θ_i) can be reflected from the core/cladding interface and fully propagated in the core only if the angle of reflection in respect to the normal is larger than the critical angle (θ_c), otherwise, the light can escape the core boundaries. The critical angle can be calculated as [13,14]:

$$\theta_c = \arcsin\left(\frac{n_{cl}}{n_c}\right) \tag{1}$$

Moreover, another important characteristic of the optical fibre which is related to the application of LTC is the numerical aperture (NA). The NA is a dimensionless quantity that characterises the range of angles that an optical waveguide can accept or emit light and can be calculated as [22,23]:

$$\text{NA} = n.sin\theta_{max} \tag{2}$$

where n is the refractive index of the medium accepting the light, i.e., fibre core, and θ_{max} is the maximum acceptance angle. As the refractive index value of the core increases, the fibre can accept light within a higher angle. However, the higher the NA value is, the higher number of modes are supported by the waveguide. As a result, high NA fibres are usually multimode fibres. For the application of LTC high NA fibres are preferred in order to couple the ambient light efficiently.

3. Optical Fibres Derived from Translucent Materials for LTC Production

The OFs are the most widely accepted, and generally employed for the production of LTC among all the light-transmitting elements, owing to their excellent light transmittance attributes. Normally, the OF is found to be made up of two kinds of materials, i.e., glass or plastic; since it can be embedded in concrete internally [24,25]. It is noteworthy that the OF sensors which are implanted into the concrete could be utilized to detect strain and deformation, vibration and corrosion of concrete [25]. Losonczi has embedded glass

OF within the concrete and introduced LTC in 2001 [26,27]. Here, the light has been transmitted through OF through the internal reflection mechanism. The use of optical fibres as translucent components in LTC preparation was primarily due to their high light transmittance properties, even at angles exceeding 60° [28]. Several factors might impact the LTC performance in relation to OF, including light transmission, mechanical properties, and durability attributes. Among the most important are fibre volumetric fraction, fibre spacing, and fibre diameter, among others. These are largely fibre volumetric fraction, fibre spacing and fibre diameter. A few researchers [29,30] have considered glass fibre in place of plastic optical fibre to examine the usefulness of LTC light transmission attributes. Overall, the prior investigations were focused mostly on mechanical and light transmittance characteristics of an LTC enclosing optical fibre [29,31–34].

Snoeck et al. [29] have utilized glass fibres in producing luminous self-healing cementitious materials and prepared the two different processes of mixing, i.e., manual insertion method and direct-mixing technique [29]. It has been accounted that manual addition was not viable for a higher quantity of glass fibres owing to the complications in not only handling, but also in placing. On the contrary, the direct mixing method was shown to be less time-consuming than other methods. LTC's strain-hardening behaviour is influenced by the macro glass fibre, while its translucency is determined by the glass fibre content and sample thickness. Altlomate et al. [35] concluded that the enclosure of the optical fibre did not have a major influence on the concrete's compressive strength. According to them, combining larger fibre diameters with greater fibre spacing in LTC would not affect its light intensity either. Additionally, the ultrasonic pulse velocity (UPV) examinations carried out have also demonstrated that the LTC was in a good-quality and homogeneous mix, regardless of the addition of optical fibre. Henriques et al. [36] executed mechanical attributes and light transmission properties relied sturdily upon the volumetric fraction of fibres [35–38]; mechanical tests on the optical fibre itself, as well as microstructure and durability performance of LTC. Light transmittance characteristics of LTC were studied and found that higher curing temperatures resulted in fibre aging, which had a detrimental impact on light transmittance characteristics of LTC were studied by Li et al. [39]. As Li et al. [40] reported in their study, Optical fibres were immersed in a silane coupling agent before casting in order to smooth out their surfaces along the fibre axis. Nevertheless, hiatuses could still be detected through the fibre and matrix interface during microstructural analyses. The optical fibres in the filamentous form had greater compressive strength and light transmittance properties than those in the bunchy form. Huang [22] studied the light presentation of building envelopes employing LTC enclosing optical fibres and determined that for light transmission function, the smoothness of the optical fibres' ends is vital. Due to their small cross-section, a small range of light accepting angles and a limited number of OFs in the concrete, the light-capturing performance of the OF is limited. Analogously, to minimise light loss during light transmission, Mosalam and Casquero-Modrego [41] used CPC—compound parabolic concentrators and SC—straight cones. They suggested that CPCs and SCs should have a half acceptance angle, which is compatible with the optical fibre's numerical aperture (NA) in order to maximize light transmission.

The numerical aperture (NA) is an important characteristic for optical fibres since it determines the acceptance angle that light may travel through, according to Su et al. [42]. They conclude that a large NA has led to increased light transmission, but it has also resulted in excessive daylighting. LTC's light transmittance was shown to be superior to NA's in terms of its influence on fibre volumetric fraction. "The low surface roughness of optical fibres results in weak interfacial bonding strength," argue Robles et al. [43]. Nevertheless, the enhancement of fibre diameter has resulted in an increase in the compressive and flexural strengths of LTC on account of the decline of the fibre-matrix interfacial area. Several researchers concentrated on the infrastructural applications of LTC, mainly for roads and tunnels [44]. In an effort to improve road safety, Saleem et al. [21] have created a transparent concrete-based smart lane divider. Fibres implanted in concrete served as both light-transmitting elements and traffic-density sensors. LTC's skid resistance likewise met the regulatory requirement for skid resistance. According to the optical fibre signal, the LTC lane divider sends a variety of light from the light source, so that drivers on the road may be aware of traffic in front of them. Zhu et al. [45] have employed LTC to improve visibility and smart traffic markings to increase safety. LEDs were used as the light source for the road markers. This study also accounted that with a reduced light intensity of the surroundings, the visible distance of LTC increased. While maintaining the same light intensity, the red light's viewable distance was the longest, followed by green and yellow light.

On the other hand, Pena-Garcia et al. [44] utilized LTC on tunnel pergolas that let the sunshine into the threshold zone of road tunnelling. Even though optical fibres based LTC is the mainly encouraging subject in comparison with other luminous elements owing to its brilliant light transmission attributes, the research on this particular area is still shallow and confined. Li et al. [40] have revealed that an examination of an examination of LTC is still in its preliminary stage as earlier investigations were largely from commercial product demonstrations. Not merely that, mechanical as well as physical characteristics of optical fibre were hardly ever tested. There exists a smaller quantity of research the revealed the physical, microstructural analyses as well as durability characteristics of LTC, besides its mechanical and light-transmitting properties. Mostly, the physical characteristics of concrete are straight to reflecting the durability and quality of a material. For that reason, durability parameters viz., permeability, water absorption owing to the addition of optical fibres, chemical resistance, UV resistance, and other resistance should be further examined prior to LTC can be functional systematically in the building and infrastructure industries. On the other hand, Kamdi [46] has concentrated on LTC production materials, mixing courses of action, usefulness, impact on the environment as well as its future scope. He mostly advocated on a thought for employing OF with good quality concrete for making transparent LTC. According to him, the reason behind the restricted industrial spread of LTC in construction lies with its availability as merely precast and prefabricated blocks and panels. In their research, Momin et al. [47] revealed that an LTC sample with OF was found to allow more transmission of light through it, than an LTC specimen with a glass rod. In this research, authors utilized moulds of sizes 150 mm × 150 mm × 150 mm for the casting of cubes of glass rods and that of optical fibres, respectively. They have noted down that light transmitted through the glass rod and optical fibre cubes as 0.25%–1.57% and 7.41–9.5%, correspondingly. However, the compressive strength of OF cubes was reported somewhat smaller than the corresponding cubes with the glass rod. The investigations on the compressive strength of two dissimilar kinds of concrete were carried out by Tiwari and Saharan [48]. In the case of type-1 concrete, they examined the normal LTC-mix, but in type-2, they supplemented 0.625% and 0.125% by mass of rice husk and steel fibre in that order. They employed OF of 0.5 mm in diameter with a different percentage ranging from 0.25–4.00% of the total volume of cubes in both types of concrete. It was observed that as the percentage of OF was augmented, the compressive strength of cubes was decreasing. Though, it is possible to increase the same by supplementing rice husk and steel fibres. In a research study by Bishetti et al. [49], the wooden mould of size 15 cm × 15 cm × 15 cm had been prepared by drilling its two faces for holding the optical fibres. The mix design ratio of concrete was kept as cement: sand: coarse aggregate—1:2.24:1.78. It was reported that as the percentage of OF enhances, the compressive strength of the LTC declines. When there were no OF, i.e., 0%, the compressive strength of concrete was 43.55 MPa, which was trimmed down to 31.10 MPa when 5% of optical fibres were introduced with LTC. Another research study by Paul and Dutta [50] on bending and compression resistance of LTC beams accounted that the behaviour of the material depends highly on the plastic OF density in the concrete element. It was assessed that the plastic OF added in the concrete will not deteriorate its resistance, amounting to 0.8% by utilizing 1.5 mm diameter possessing plastic OF and 0.4% steel fibres. More to add, plastic OF can be connected with the concrete and they are also capable to keep the conditions of bending and compression resistance.

What is more, Nagdive and Bhole [51] have estimated the characteristics of Plastic Optical Fibres (POFs) based concrete. They reported that the quantity of the light transmitted through the sample is found directly proportional to the ratio of the volume of the POFs to the concrete. The thickness of the elements is less significant on the condition that the direction of placing the POFs does not greatly run off an angle of 90°. It is quite significant that the POFs cannot refract at any point, since then they lose the capability to transmit the light.

Mahadikhani and Bayanti [52] explained the utilization of OF in different sensors viz., stress and temperature sensors, and bridge monitoring. They accounted that the fibre optic sensors can productively be employed for the monitoring of structures. The non-destructive examinations of the members under long-lasting service loads, with the capability to caution against impending failure, are other utilizations of fibre optic sensors. Commonly, fibre optic sensors demonstrate higher sensitivity and accurateness in average strain, stress and temperature measurement in structures.

Kurpińska [53] researched the LTC manufacturing techniques, whereby she produced samples of LTC enclosing POFs having 0.7–1.2 mm diameter and 2.5% density. Additionally, she perceived that the referred density made possible good-quality light conductance, where the element thickness was immaterial. Not merely having that, the compressive strength of the LTC blocks was ranging between 50–80 MPa.

4. Light Transmitting Concrete Manufacturing

Two basic materials are needed for manufacturing light transmitting concrete or smart transparent concrete, i.e., one from sensing and another from the construction field. Here, optical fibre is employed as a sensing and optical transmission element. The production procedure of the standard transparent concrete block can be portrayed as follows:

Firstly, some holes with orthogonal arrays are being drilled in the plastic sheet following the volume ratio of POF and concrete (Figure 2). Secondly, POFs are placed through the holes of two plastic sheets that are fixed on the slots of wood formwork and lastly, a specific concrete mix is poured into the formwork and vibrated thoroughly on the shaking table.

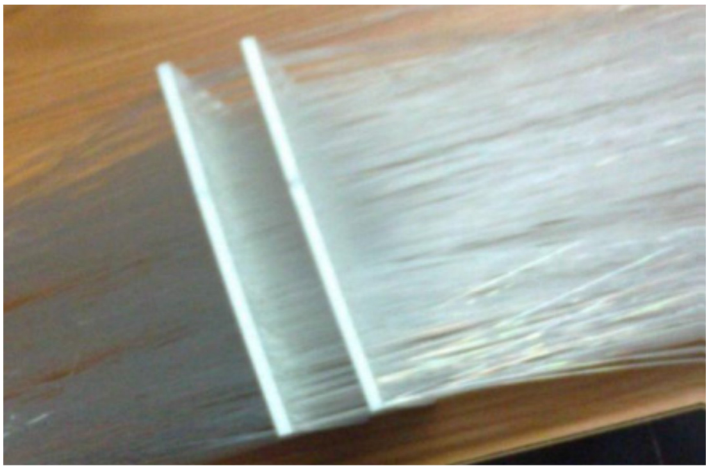


Figure 2. Optical fibres arrangement [54].

5. Properties of Light-Transmitting or Translucent Concrete

5.1. Durability

In general, concrete as a building material should exhibit acceptable durability properties for structural construction prerequisites. The durability of concrete is the material's competence to resist deterioration owing to chemical attack, abrasion, weathering, or various adverse environments while keeping its integrity of strength and look all through its service life [55,56]. Significantly, the permeability of concrete is highly susceptible to exposure to gases, water, and ions from the neighbouring environment [57]. Therefore, the durability examination results of LTC are highly essential (Table 1). For this purpose, the durability investigations of LTC were conducted in the past based on a kind of translucent element utilized in manufacturing the LTC. For illustration, it is an identified fact that glass is susceptible to ASR–alkali–silica reaction while it is exposed to an alkaline environmental condition. For this reason, Pagliolico et al. [58], as well as Spiesz et al. [59] have carried out ASR examinations on LTC produced using glass as a translucent material to verify the durability of the referred LTC. What is more, Pilipenko et al. [60] have concentrated on tests concerning LTC manufactured with polymer epoxy as light-transmitting material viz., permeability, colour fade resistant, freeze–thaw resistance, water absorption, and chemical resistant. On the other hand, anions were employed as a transparent element in Saleem and Blaisi's study [61], which examined the impact of anions on the structural durability of reinforced LTC structures. Moreover, Henriques et al., 2020 [62] have mostly thrown lights on tests of permeability, porosity and water absorption of LTC enclosing optical fibres. The supplementation of optical fibres produces more voids inside the concrete on account of the feeble interfacial bonding amid the concrete paste and fibres. More to the point, it is a known fact that polymethylmethacrylate (PMMA), which is the most widely used polymer for POF, is susceptible to ultraviolet (UV)-radiation, whereby it alters the chemistry of the OF and leads to poorer mechanical strength and weaker light transmission. Taken as a whole, the centre of attraction of past researchers was lesser to investigations on durability attributes in comparison with the mechanical and light-transmitting properties of LTC.

5.2. Mechanical and Physical Properties

With a view to measure the mechanical properties of LTC, investigations on flexural and compressive strengths had been carried out. According to Altlomate et al. [35] along with Kumar and Ahlawat [34], the compressive and flexural strength of LTC specimens revealed relatively lower values compared to the reference [62]. Luhar et al. [63] reported that the compressive strength of LTC was approximately equal to the corresponding of ordinary Portland cement (OPC) concrete. In their research study, they employed the "Plastic Optical Fibre" possessing 1 mm diameter for transmission of light and placed them at the distance of 8 mm horizontally. The OPC concrete was utilized for the development of 70 mm × 70 mm × 70 mm-sized concrete blocks. Authors have noted down the average compressive strength of standard concrete cubes as 39.50 MPa, while the corresponding value of LTC (optical fibre 5% of cementitious materials) was recorded as 36.70 MPa. Hence, their research work has made it obvious that transparent concrete can be promoted for structural construction work sans any apprehension concerning compressive strength. This is an important step to endorse LTC as a potential durable unique building material for construction and infrastructure industries. Tuaum et al. [64] have kept the centre of attention on LTC facades panels in order to estimate their structural performance. The mechanical properties viz., flexural strength, compressive strength as well as flexural toughness were investigated on LTC manufactured using OF. The compressive and flexural strengths were reduced due to the addition of OF, but the flexural toughness of LTC was met with 11% to 12% elevated values in LTC compared to the conventional concrete panels. This was the indication for enhanced energy absorption as well as ductility of LTC compared to standard concrete. Typically, the supplementation of the luminous elements slims down the compressive strength of resultant LTC, irrespective of the kinds of translucent elements used. The mechano-physical properties of the translucent materials should be recognized prior to incorporate them in the concrete mixture since the characteristics of the translucent materials influence directly the properties of the entire concrete mix. For instance, following the study of Henriques et al. [36,62], the OF is hydrophobic and smooth, a fact that contributes to weaker bonding amid a fibre matrix interface. An LTC enclosing recycled glass also displayed the analogous quandary owing to the pitiable geometry particles of glass and feeble adhesion amid the cement paste glass and glass as found in the investigations of the interfacial bond strength decides the attributes of heterogeneous systems like LTC as to Zhandarov et al. [65]. Numerous research works had been conducted to investigate the fibre-matrix interfacial bond strength for fibre-reinforced concrete. Fibres of steel, polypropylene, brass, as well as natural fibres, were studied by Drechsler et al. [66] for the bond strength at an interfacial zone of fibre-matrix since the bond strength impacts the durability, failure behaviour and mechanical attributes of the structures of concrete. According to Li et al. [39], they used a silane coupling agent to improve the interfacial bonding strength between fibre and matrix. They found that the silane coupling agent could not be relied upon to increase the binding strength as expected. Despite this, there are only a few investigations on the interfacial bonding strength between elements and matrixes. Concrete's quality and durability depend on the LTC's physical characteristics. Even though, the concerning literature is inadequate on the physical properties of LTC as accounted by [2,35,37,60], which normally included criteria to recognize the physical properties of concrete such as fresh concrete workability, ultrasonic pulse velocity (UPV), pore ratio and concrete density.

5.3. Light-Transmitting Property

For the most part, researchers have carried out light transmission tests of LTC on diverse variables. Still, there are no guidelines and standards established for examining the light-transmission property of LTC. An experimental setup and the test apparatus varied among the researchers, e.g., the experimental setup for the light-transmission examining can be either in the encircled area according to [47,59] or maybe in open space. Altlomate et al. [35] made an encircled area for LTC luminance examination for putting a stop to the scattering of light and to make certain all light rays from the light source are engaged to the samples. Even though the discrepancy in measuring equipment may not have a significant impact on luminance measurements, the information obtained is unique because of the uncertainties introduced by the precision and resistance of the measuring equipment. For this reason, some researchers such as Mainini et al. [18], and Spiesz et al. [59] have confirmed a light-transmittance ratio that minimizes measurement errors caused by different measuring equipment. A small number of preceding investigations on the light-transmitting characteristic of LTC have made known that the said property is found directly proportional to the augment of optical fibres ratios and their diameter. An earlier study simulated and studied through experiments in specimen archetypes of concrete panels [58]. Consequently, the diminution range in energy demand for lighting was computed in simulations from 12.7% to 16% with light-transmittance as 5%. Even better utilization of investigated concrete panels was for internal walls instead of for envelope components. The significance of confirming the volume ratio of the fibres in LTC panels and its impact on day-light transmission attributes; the transmitted luminous flux by employing 2 and 3 mm optical fibres with dissimilar volume ratios were examined [67].

The light-transmitting aptitude for six samples enclosing plastic optical fibres possessing diverse diameter, volume ratio, and spacing was investigated through experiments. Logically, light-transmitting enhanced with the percentage of plastic optical fibres. The fibres can improve the transparency appearance; the optimum result of luminance was found when 1.43% of fibres possessing 1.5 mm diameter were employed and the distribution of fibres was at a distance of every 10 mm.

5.4. Thermal and Energy-Saving Properties

Translucent or light-transmitting concrete is considered as a green material that is competent enough to trim down energy consumption by dropping the exigency for the electricity brought into play for human-made lighting during the daytime as well as also for heating loads in the wintry weather [67]. A translucent concrete panel has been experimentally studied for the light transmissions and thermal attributes by modelling the orientation of the optical fibre into the concrete in the course of exposure to simulated sunlight for 1 year. The outcomes demonstrated the good thermal and mechanical characteristics of LTC [14]. The computational modelling for an LTC panel was designed to explore the light-transmission property in the model with the climatic conditions prevailing in Berkeley, California, applying a fibre volumetric ratio of 10.56%. Subsequent to more than one year's simulation, an algorithm was applied to simulate and calculate the absorption of solar heat by the LTC panel. The upshots of the investigations were useful to set a method for calculating the quantity of sun-light incoming the building applying LTC, which will impact potential design decisions throughout the heating, ventilation, and air conditioning (HVAC) design course of action. A novel research study by Ahuja and Mosalam [14] was carried out on thermal and lighting analysis and also to obtain the optimum ratio of optical fibres for LTC panels which will be attained the highest energy-saving. This research relies upon producing the panels in the lab with the identical dimensions of the computational model in an earlier study, applied to a model room. The software was developed to perform the simulations and the calculations of the heating and cooling loads on the heating, ventilation and air conditioning (HVAC) system and other light and thermal analyses, to determine the optimum ratio of optical fibres for panels, which will accomplish uppermost energy-saving. They uncovered that the use of a fibre volumetric ratio of almost 6% was reducing the energy consumption by 18%. Recently, there was a research investigation study on the formation of an experimental apparatus for carrying out the thermal conductivity and transmittance examinations in an LTC block possessing a 4.1% fibre percentage. This research revealed that LTC conducts lesser heat than the reference concrete. The thermal conductivity coefficient for the reference concrete is 1.75 W/(mk), while for LTC, it is 1.61 W/(mk). The results disclose that the adding up of optical fibres in the concrete results in a superior thermal insulator. A new-fangled LTC panel was investigated by Pagliolico [58] using a higher resistance self-compacting mortar with coarse flat glass wastes. Based on calculations, the energy demand for lighting declines as the light-transmittance value of the LTC panels is augmented. This reduction was found in the range of 6% to 20%. Furthermore, Juan and Zhi [2] have studied experimentally and numerically the properties of light-transmittance and mechanical, as well as the thermal performance of a novel kind of resin translucent mortar-based concrete [42]. The research pointed out that LTC has 0.38 W/(mk) thermal conductivity, which is 60% lower than the standard concrete of 0.89 W/(mk).

5.5. Microstructural Properties

The microstructural analyses unveil the structure of concrete matrix microscopically to verify the concrete's strength and durability through testing its porosity and permeability. Based on limited previous literature on LTC, merely a few researchers have endeavoured for micro-structural analyses to obtain a better understanding of the said two parameters for LTC durability. Henriques et al. [36] have investigated LTC manufactured with optical fibres and showed that there were hiatuses amid the matrix and fibre interface. These examinations have made it known that the decline in the context of compressive strength of LTC was assigned to the poor bond strength amid the concrete mixture and fibre.

Table 1. Translucent optical fibre components provide an overview of the current LTC database.

Refs.	Mechanical Performance	Durability Performance	Light Transmission Performance	Microstructure Performance
Altlomate et al. [35]	With an addition of a fibre percentage, the compressive strength improved.		A higher transmission might have a greater diameter, larger spaced and smaller volumetric fractions.	
Bashbash et al. [68]	A Concrete with a greater fibre diameter has a better strength when the volumetric percentage of the fibre is constant. With an increase in fibre volumetric percentage, LTC's flexural strength is somewhat less.			

Table 1. *Cont.*

Refs.	Mechanical Performance	Durability Performance	Light Transmission Performance	Microstructure Performance
Huang [22]			The smooth fibre's end ensures an effective transmission of light.	
Henriques et al. [36,62]	The compressive strength difference is negligible for the fibre volumetric fraction between 0 and 2 percent.	The increase in the volumetric percentage of fibre enhanced the water absorption of concrete.	Increased light transmission with a rise in the volumetric fibre fraction.	At the fibre-matrix interface, the presence of voids was observed.
Huong and Kassim [38]	The increase in the fibre volumetric fraction improved the compressive strength of LTC.		With a greater volumetric fibre percentage, the light transmission of LTC is increased.	
Henriques et al. [36,62]	Compared to a reference sample, the compressive and flexural strength of the sample with 5 percent fibre volumetric fraction was reduced by 20 percent and 25.4 percent, respectively.	Porosity and water absorption of the concrete were enhanced by adding fibres.	As compared to LTC with a 3.5 percent fibre content, LTC with a 5 percent fibre volumetric fraction increased light transmittance by 100 percent.	Amid the fibre-matrix interface, voids were found.
Jiménez-Muñoz and Fernández-Martínez [69]	With a fibre volumetric fraction of more than 2 percent, the compressive strength of concrete was reduced.			
Kumar and Ahlawat [34]	The addition of optical fibres does not impair the concrete compressive strength.		Higher transmission of light using a high volumetric fibre.	
Li et al [39]	The transmission ratio rises and the compressive force decreases with an increase in optical fibres content.		By means of a parallel arrangement along the light direction, LTCM obtains a good transmission ratio with an adequate optical fibre filamentous.	In contrast to filamentous fibre, the junction of cement mortar and fibres was not fixed. Bunches of fibres have gaps in them.
Li et al. [40]	As a result of the optical fibre, the concrete's compressive and flexural strengths dropped.	The flexural and compressive strength is increased when samples are cured at elevated temperature.	After being cured at an elevated temperature, the light transmission of optical fibre is reduced.	Many voids surrounding the fibre matrix interface have been identified.
Li et al. [39,40]	LTC having lower compressive strength than ordinary concrete.		The optical power inclines to be the same for specimens with varied fibre numbers when the optical power distance reaches a specific range.	Through the loss of dispersion, the surface roughness of the end side of the fibre impacts the emerging light transmittance.
Mosalam and Casquero-Modrego [41]			As long as the optical fibre has the same volumetric proportion, it will transmit more light.	
Robles et al. [43]	Flexural and compressive strength were improved as a result of the increased fibre diameter.			
Saleem et al. [30,61]	An ideal volumetric fraction of the tendon fibre is 3 percent to minimize compression loss.		Increasing the POF tendon ratio may improve light transmission.	
Salih et al. [70]	Adding optical fibers reduced flexural strength by a significant amount. The compressive strength of LTS is lower than normal concrete.			
Shen and Zhou [32]			The simulation showed that LTC can cut light energy usage by roughly 20%.	

Table 1. *Cont.*

Refs.	Mechanical Performance	Durability Performance	Light Transmission Performance	Microstructure Performance
Snoeck et al. [29]			LTC's transparent effect is commensurate with the volumetric fibre fraction. The assortment of 3% of glass and 2% of PVA fibres has a transparent effect of 4.71%.	
Shitote et al. [71]			Distance and numbers of fibres affected the overall light transmission.	
Su et al. [42]			Light transport properties are more influenced by fibre volumetric fraction than numerical aperture.	
Sawant et al. [72]	With increased fibre content, compressive strength dropped.		With the increase in fibre, the light transmission increases.	
Taneja et al. [37]	As compared to conventional concrete, LTC does not lose strength with specific quantities of fibre.		Transmission of light via optical fibre is proportional.	
Tuaum et al. [64]	With increasing fibre volumetric fraction, compressive strength increased.			
Ugale et al. [31]	By substituting the fine and coarse aggregates with marble powder waste and waste marble, the maximum LTC compressive strength can be obtained.		LTC with marble dust waste and aggregate has a greater light-transmitting capacity as compared to LTC with marble aggregates only.	
Zhu et al. [45,57]			Light is spread through the larger fibre diameter.	

6. Global Application of LTC

The LTC has excessive potential to be employed for buildings and infrastructures; however, the investigations on LTC are still in an initial stage and its industrial application is currently less competitive than other new innovative construction materials [67]. Still, the data of the scientific research and implementation is deficient, since there exists merely a few studies [44,45] in the breathing research on the application of LTC in construction and infrastructure sectors, pointing towards the need for further exploration of LTC in depth.

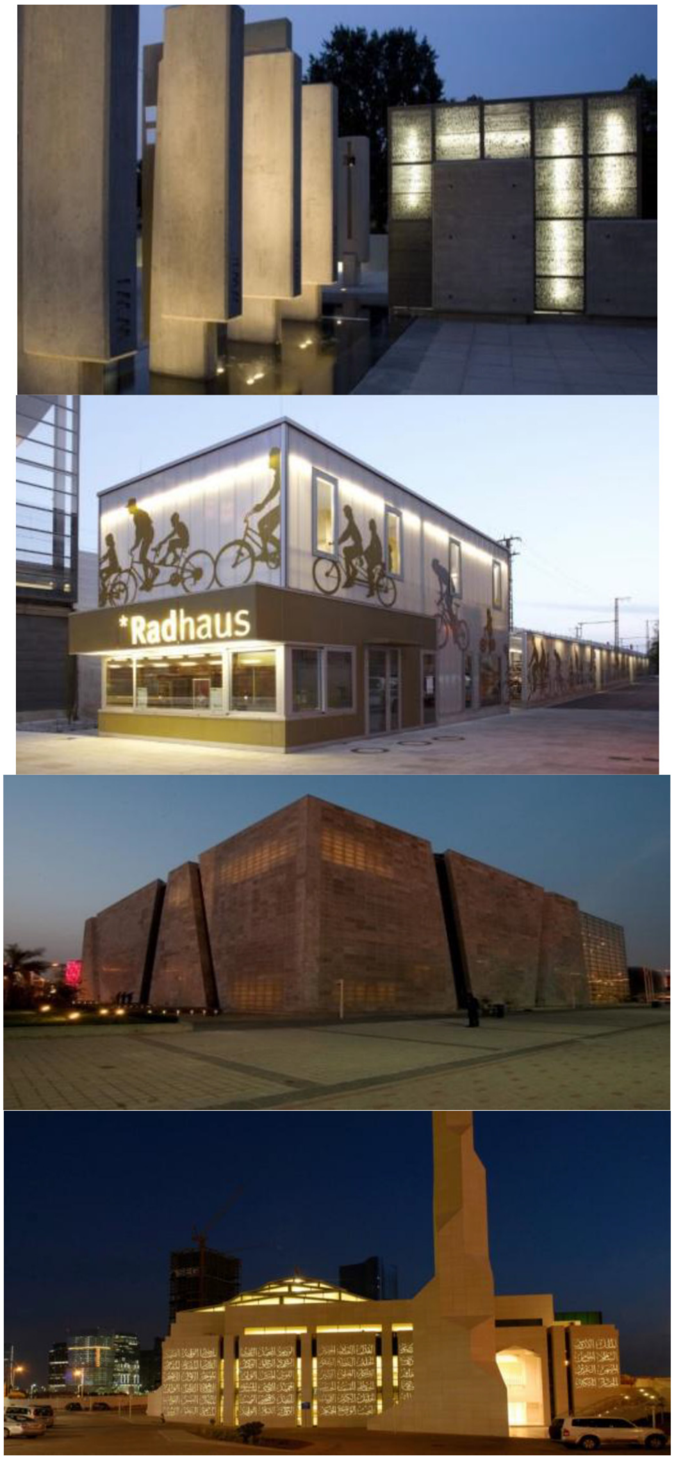
Not merely those examples mentioned earlier, a few potential uses of LTC were also suggested in the literature; however, they are yet to be constructed practically and accepted widely. Besides the use for aesthetic purposes and reducing the light energy consumptions, LTC can also be employed to guarantee safety, security and supervision in infrastructures of banks, prisons and museums too, as suggested by Tuaum et al. [64]. The reason behind it is the usual thicker walls of the prisons in the interest to achieve the impact resistance prerequisite, which consequences in a dark atmosphere and depreciates the basic health conditions of the prisoners and serving staff inside. Azambuja and Castro [73] have utilized LTC to create prison walls that are intended to encourage not only better-living circumstances, but also to trim downlight energy consumption inside the prison. Furthermore, the high-rate lighting system is essential inside tunnels in order to get better visibility and safety in the tunnels. Since LTC owns the potential to illuminate, it can be used to construct tunnels and dark subway stations. LTC is used to create a mock-up system for tunnel pergolas, but no additional research has been conducted on this application in terms of luminance level or mechanical requirements. Qin et al. [74] have talked about the study on solar optical fibre systems, which is implemented in Huashuyan Tunnel in China. To illuminate the highway tunnel from the outside, the solar optical fibre system used optical fibres as light pipes. When used as light pipes in LTC, optical fibres may be used to create tunnels that transfer light into them, resulting in a superior lighting system within. Nevertheless, the design, production courses, mechanical attributes and luminance level of LTC necessitate advanced investigations prior to being adopted for this objective.

Moreover, the uses of LTC also include viz., as a façade material in numerous fine architectural monuments; LTC blocks used for floorings and pavements, roads, tunnels, speed humps, staircases, sidewalks, desks, etc. and in dark location constructions where it is needed to illuminate in order to provide visibility and safety for people and traffics; besides for architectural and to add the beauty of the interior by illuminating the area in daytime; as well as in partition walls, doors and panels, etc., as building materials, for lighting up dark places or windowless areas such as basements. In LTC partitions or partition walls in the office cabins or the houses, in making attractive furniture, and intelligent light fixtures, to lighten the dark subway stations, etc., its use is appreciated [16,18,75]. However, sorry to say, currently there are only a few global manufacturers of LTC. LTC not only retains the higher density top layer, but is also frost and de-icing salt resistant, making it strongly recommendable in cold climate nations. More to add, it stands under the fire protection classification as A2 and contributes very elevated UV resistance. The applications of LTC in the construction sector are shown in Figures 3 and 4.

Figure 3. Application of LTC in Italian Pavilion [2,76].

Japan

Figure 4. *Cont.*



USA

Germany

China

United Emirates

Figure 4. *Cont*.

Germany

Figure 4. Characteristic applications of LTC [2,35].

Although the LTC applications are restricted, there are still a few memorable and eye-catching global projects erected with this type of concrete, which might serve as references for further development and investigations on LTC. For illustration, the Italian Pavilion at Shanghai Expo 2010 is built utilizing LTC manufactured with the addition of polymer resin. More to the point, the partitions and walls of LTC in Bank of Georgia, and translucent facades in the Aachen University, Germany as well as The Al Aziz Mosque in Abu Dhabi [28], were all built with panels of LTC. In addition, a German company is known as "Lucem Lichbeton" had pioneered the LTC pavements and walkways. One more recently constructed "Stuttgart City Library" in Germany is popular for its cube-shaped translucent roof, which permits the natural light to illuminate the area. The biggest project demonstrating the LTC concept is an artistic installation known as the "European Gate" built in 2004, in Hungary [12], which was designed in memory of the celebration of joining the European Union (EU) by Hungary. It is located at the public entrance of "Fortress Monostor" in the town of Komarom, Hungary. It is one of the most impressive and remarkable pieces of art conjugating visual lighting display. During the day, the LTC blocks of this road look like concrete pavement; however, during sunset moments, it starts to shine due to the light sources placed underneath them. A ringed light pattern took shape around the main square as when it is dark.

7. Pros and Cons of Translucent Concrete

The applications of LTC 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 LTC walls using free natural sunlight. The optical fibres also function as heat insulators, and hence, they are very effective in countries with cold weather. A solid wall of the house, when imbued with the capability to transmit light, will use fewer lights during daylight hours. LTC owns architectural properties for contributing an excellent aesthetical view to the building. LTC application in constructing buildings saves energy consumption because it is eco-friendly owing to its light-transmitting attribute. Thus, it is obvious that LTC is a great potential tool that is competent enough to save electricity and cost as well.

The key disadvantage of LTC includes its higher cost due to the use of expensive optical fibres. Moreover, the casting work of LTC blocks can be tricky for unskilled labour, therefore skilled people are needed, thus augmenting once again the financial budget for its manufacture. For these principal reasons, i.e., the pricey glass optical fibre's cost and the complication of installation of fibre, LTC is still not widely utilized for constructions as an innovative building material. Apart from these two key drawbacks in the path of across-the-board applications of LTC in infrastructure and construction industries, there exist some other reasons such as lack of dependable advanced investigational information on durability as well as mechanical attributes of it to be examined for its entire service life period. Not only have that, but the design of such LTC also needs to be developed further.

8. Conclusions and Discussion

The revolutionary edifice product, i.e., light-transmitting or translucent concrete, seems to be quite a unique and innovative variety of building material for the novel concept of "Green Architecture". The transparent concrete possesses a good-quality light-guiding attribute which contributes to the very significant property of the aesthetical view. It can be useful for the best architectural appearance of the building. The ratio of optical fibre volume to concrete is found to be proportional to its transmission. Praiseworthily, it can be of great use where the light cannot reach with apposite intensity. This new-fangled construction material can put together the concept of green energy saving with the utilization of self-sensing characteristics of functional materials. The blocks of LTC can be utilized in several ways and implemented into plenty of forms proving it as highly valuable. Merely the economic issue of being a little expensive will not be able to stop this high-class architect material from using and promoting it as a promising building material for the future for a longer period. Truly, LTC appears to be a great sign of artistic evolution together with an attraction too. Apart from its environmental and economic benefits LTC makes architecture more visually appealing, thus, increasing the overall aesthetic value of the structure. Besides the beauty aspects, LTC also presents security and supervision, e.g., big houses or infrastructures having bigger security walls are frequently found with lower safety and security norms. LTC is greatly useful for this type of function as well as for prisons, schools, colleges, universities, museums, etc., and other places where safety and security are highly necessitated. This concept will contribute to an easier accreditation of "Green buildings" under daylight savings. Huge sky-scraping towers for offices and corporate infrastructures can share the lighting when the ceilings are translucent. The properties of LTC include not only energy savings, but also heat insulation, making it the future tool for days to come. The future of LTC as a building material seems very bright, and its distinctive light-transmitting property is going to make it doable with a view to a reduction in power consumption to prove it suitable as a green replacement of traditional concrete in the future. This review concludes that LTC is a smart way of optimizing and using the free day-light system in an intelligent way of the "live and go green" concept in the form of a potential, novel, promising innovative, and bright future possessing building materials that enhance the aesthetic look, energy-saving, etc.

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