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Mechanical, light transmittance properties and simulation study of sustainable translucent lightweight aggregate concrete

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**Abstract**

To investigate the engineering feasibility of translucent lightweight aggregate concrete (TLAC) in sustainable buildings, this paper focuses on testing the light transmission properties and mechanical performance of TLACs, the light transmission effect in building interiors is simulated and evaluated using automated steps seamlessly integrated with REVIT software and Radiance software. The preparation process of TLACs and the mixture proportions of raw materials were designed by combining translucent concrete technology with self-compacting mortar. The results indicate that the light transmission of TLAC increases with the volume of polymethylmethacrylate optical fiber (POF) incorporated and the diameter of POF, while the compressive strength tends to increase first and then decrease with the increasing volume fraction of POF in the TLAC samples. Moreover, the building lighting simulations show that indoor illuminance will improve significantly with the use of TLACs, which further illustrates the energy savings and structural performance improvements owing to the application of TLAC as a modern construction material.

**1. Introduction**

Sustainable construction is becoming a significant and emerging issue for the construction industry around the world [1–3]. The development of sustainable architecture plays an important role in environmental protection by minimizing the consumption of raw materials and energy and promoting the practice and design of buildings in an eco-friendly way. The most important and widely used building material in the construction industry is concrete [4–6], a kind of completely opaque material. Nevertheless, it is possible to change concrete from opaque to translucent by combining optical fibers with a concrete matrix [7]. Translucent concrete (TC) is a new energy-efficient building material that transmits light into the indoor environment via embedded optical fibers [5, 8, 9], which provides new insights into the interior design of buildings and decorative architecture [10]. TC not only improves the lighting of the building and reduces energy consumption for lighting, but also changes the traditional pattern of dense, dark, and bulky monotonous building walls, making the building aesthetically pleasing and decorative [11]. In addition, lightweight aggregate concrete is a new type of concrete prepared by replacing the aggregates in ordinary concrete with natural or artificial light aggregates. In comparison with ordinary concrete, lightweight aggregate concrete shows advantages in lightweight, high strength, good thermal insulation, and strong fire resistance [12], and is widely used in high-rise buildings and large-span building structures [13].

Recently, lightweight aggregate concrete and translucent concrete have been widely used worldwide to guarantee the sustainability of modern building construction [14–18]. The light transmission mediums in the translucent concrete are important for the light transmittances and costs, the POF shows high potential in daylighting systems because of its high transmittance and low cost. Navabi et al. [11] investigated the optical and physical properties of high-performance light-transmitting concrete prepared from Portland cement, POF, silica fume, and fine aggregates. The results showed that the compressive strength of the light-transmitting
concrete specimens decreased with the increasing volume fraction of the optical fibers. The optical power increased non-linearly with the increase in the number of optical fibers. Raghava Maheddhar et al. [19] investigated the compressive behavior and light transmission capacity of translucent concrete. With the replacement of fibers in the concrete volume (0.10%–0.20%), the compressive strength was found to increase by 3% and the maximum amount of light passing through the cube was 2122 lux. Huang et al. [2] analyzed and discussed the constructability issues including mechanical and optical losses. Numerical models of the single OF and the whole TCP were developed using ray-tracing software to analyze the light transmission mechanism. Altomate et al. [4] investigated the performance of Light Transmissive Concrete (LTC) specimens made using different doses and spacings of POF. The performance of POF was investigated and discussed. The experimental results show that LTC can provide a high light transmission rate. In addition, the use of POF in concrete can lead to an increase in compressive strength. Said’s research [8] has shown that it is convenient to exclude coarse aggregates from the ingredients of a mixture for the manufacture of ‘light-transmitting cement mortar’ to obtain better homogeneity and compaction, which gives TC better light transmission. On the other hand, due to the vibrating of concrete, there are concerns of missing the optical fibers alignment. To get rid of this problem, self-compacting concrete is the best solution for TC fabrication with good homogeneity. Consequently, much attention is paid to the freshness and hardening properties of self-compacting concrete in order to make it cleaner and more sustainable, either by replacing fine aggregates with industrial by-products or by adding steel or polymeric fibers [3, 20, 21].

The rapid development of Building Information Modeling (BIM) technology to art buildings has provided great support for sustainable architecture as shared knowledge and information source that enables the integration of multiple parametric information base resources, providing a reliable information basis for all decisions throughout the life cycle of that construction project from conceptual design to end-of-use demolition, which also can be retrieved to perform different analyses on buildings, such as energy analysis, daylighting analysis, cost estimation, and structural analysis [22]. The REVIT software is compatible with energy analysis software commonly used by architects to simulate or measure complex shading and daylight control systems using interactive analysis methods to analyze the effects of building daylighting in real-time design progresses, the results become more detailed and can predict the effects of different design options, guiding and helping designers to choose the best one [11].

Materials with light-transmitting properties can be used nowadays to decrease the use of non-renewable energy sources, thus reducing the energy footprint. For this reason, innovative materials are constantly being developed to fulfill the requirements of green architecture. In this paper, fine aggregate (shale pottery and river sand), cement, POFs, and polycarboxylate superplasticizer (PCE) were used as the main materials to prepare TLAC samples. The optical power method was used to investigate the light transmission properties of TLACs at various visible wavelengths (400 nm—1000 nm), and the mechanical properties of TLACs were analyzed by examining the compressive strength at different curing ages (7 d and 28 d). Furthermore, the simulation and quantitative analysis of indoor lighting of buildings were carried out using REVIT software and Radiance software to provide a reference for the material formulation and design of this type of concrete, which will help the engineering application and research application of this type of concrete.

2. Materials and methods

2.1. Materials

The cement used in this experimental study is P·O 42.5 Portland cement (OPC) complied with GB 175-2007, the river sand (RS) from Huludao, Liaoning is used as fine aggregate. Moreover, shale pottery (SP) is used to replace RS in the preparation of self-compacting lightweight aggregate mortar, and the substitution ratio was 30% [23, 24]. The chemical compositions of OPC and SP are listed in table 1. The physical properties of RS and SP are summarised in table 2. The particle size distributions of RS, SP, and OPC are shown in figure 1, respectively. The PCE produced by Nanchang Science and Technology Co., Ltd was used as a chemical admixture to improve workability and maintain the rheology of fresh self-compacting mortar (SCM) mixes in this study solid content of 20% and water reduction rate of $\geq 25\%$ [21, 25]. The POF of different diameters (0.5 mm, 1 mm) and different volume incorporation ratios (2%, 3%, 3.5%, 4%, 5%) were used to prepare the TLAC samples [3, 8, 26]. The fiber tensile strength was 20 N, the bending diameter was 10 times greater than the diameter of the POF and its operating temperature was from $-20 \degree C$ to $70 \degree C$. Also, tap water was used in all experiments in this paper.

2.2. Sample preparation

The POFs were cut into specific lengths to be used in the TLACs, and then the optical fibers were arranged in pre-prepared molds using homemade molds for the TLAC. After several trials, the optimum mix ratio of
self-compacting cement mortar was determined, the OPC was mixed with RS at a mass ratio of 1:2, the water-reducing agent was 1.5% of the total cement dosage, and the water-cement ratio was 0.4. Also, 0.1% hydroxypropyl methylcellulose by mass of OPC is used as the viscosity modifying agent to prevent segregation of fresh mortar. The detailed mixture proportions of TLACs are shown in table 3.

A mortar mixer complying with ASTM C305 was used for preparing all SCM mixtures. The mini-slump test and the mini V-funnel test were used to describe the flowability and viscosity of mixtures in the fresh state, respectively. Fresh mixture tests show that it is possible to produce TLAC mixtures with self-compacting properties, which are filling ability conforming to the requirements of EFNARC as shown in table 4.

A mortar mix was injected into the mold without any external vibration, then the surface of the mold was smoothed out and the mold was demolded after 24 h of curing at room temperature, then the specimens were cured for 28d under standard curing conditions (temperature $20 \pm 2^\circ$C, RH $95 \pm 5\%$). The specimens were
cut with a cutter to a size of 15 cm × 15 cm × 15 cm, with a neatly cut translucent surface, and were used for light transmission and mechanical properties. Figure 2 illustrates the preparation of a TLAC sample. In addition, the light transmission properties are mainly evaluated in terms of their light transmission rate, and the surface is polished with coarse and fine sandpaper before the light transmission rate is tested [29].

2.3. Testing methods

2.3.1. Test method for light-transmitting properties

The light transmission properties of TLAC are mainly evaluated in terms of the light transmission power. To study the light transmission properties of TLACs under different lighting conditions, six groups with POF volume ratios as 0%, 2.0%, 3.0%, 4.0%, 5.0% in the same diameter of 0.5 mm, and POF volume ratio as 3.5% in the diameter of 1.0 mm were investigated, respectively [30].

The transmittance was once measured by way of the Newport 835 Optical Power Meter made in the USA, the photosensitive location of the probe was once 1 cm² and the wavelength was once in the vary of 400–1100 nm. The incandescent lamp with 500 W used to be chosen to grant light. Three areas of the obvious concrete had been randomly chosen to test the transmittance, and the variety of fibers included in every place must be the same. While the technique used to be repeated in three chosen regions, the incident mild electricity and transmission mild electricity were once examined concurrently at every step [31].

The transmittance is the ratio of the total energy derived from plastic fiber on the transmission surface to the total energy received by the incident surface [31]:

\[ \text{lt TLAC} = \xi \times \frac{J_1}{J_0} \times 100\% \]

where \( \text{lt TLAC} \), \( \xi \), \( J_1 \), and \( J_0 \) are transmittance, correction coefficient of measurement equipment, transmission energy, and incident energy, respectively.

2.3.2. Test method for investigating compressive strength

To measure the mechanical properties of TLAC, investigations on compressive strengths had been carried out. The compressive strength of TLACs was determined using specimens at 7 d and 28 d of curing according to ASTM C109. An average of three measurements was reported as the compressive strength of the TLAC specimens. The loading direction of the machine is perpendicular to the direction of the POF arrangement in cubic specimens incorporated with a constant rate of loading of 0.25 MPa sec\(^{-1}\).

2.4. Daylighting simulation

2.4.1. Analysis principles, methods, and indicators

The evaluation criteria for natural light in the REVIT software is based on the Building Light Design Standard GB50033-2013, which stipulates that the light coefficient is based on the model of a fully cloudy day. The sky
brightness distribution is relatively stable, with the zenith brightness being three times the brightness near the horizon. The simulation uses REVIT simulation software to model and calculates the indoor lighting, to analyze and determine whether the lighting effect of the main indoor functional spaces of the building using TLAC meets the requirements of GB50033-2013, to study the light transmission of different wall materials and different time points based on the summer solstice (June 21st), and to come up with the best design principles for indoor lighting of the building To create a comfortable indoor light environment and reduce energy consumption. For the calculation of the lighting coefficient, the software uses a point-by-point illumination simulation method. This means that for each room of the building model, at a height of 0.75 m from the ground, the basic parameters affecting the lighting conditions, such as interior materials and external shading buildings, are set. The Radiance commands are executed automatically by the Revit2Radiance Add-ins [22].

2.4.2. Building generalization and model establishment
A villa building with a total floor area of 229.93 m², facing south, with three stories and a height of 3 m. The floor area of the ground floor is 121.92 m², the floor area of the first floor is 69.66 m² and the floor area of the ground floor is 38.36 m². The design illuminance of outdoor natural light is 13,500 l×, and the light climate coefficient is 1.10. To conduct a clearer analysis of indoor lighting, the design illuminance of outdoor natural light is 20 l× on sunny days and 0 l× on cloudy days, while the direct solar radiation intensity is 825 W m⁻² on sunny days. The indirect solar radiation intensity is 125 W m⁻² on sunny and cloudy days.

According to the Building Light Design Standard GB50033-2013, the standard value of the present value of the light coefficient of the rooms with side lighting is 2.2%. When building the model, firstly, the model needs to be appropriately simplified according to the needs of the study, with optical analysis as the main purpose. For rooms in public buildings, non-functional rooms including corridors, toilets and lift rooms were set up uniformly as corridors in the parameter setting. Therefore, the seamless link between Revit and Radiance was used to create a 3D building model for light transmission simulation analysis.

2.4.3. Parameter settings
The application of REVIT simulation analysis requires, in addition to the creation of an accurate and suitable spatial model, the setting of reasonable control parameters. These parameters affect the timing and accuracy of the simulation and include the selection of material parameters and the selection of parameters to control the accuracy of the simulation. For the material parameters selected from the software’s material library, this simulation set the degree of window and door contamination as ‘general’, the wall material selected TLAC, the construction of the glass for 12 mm ordinary transparent glass, visible light transmission ratio of 0.72, visible light reflection ratio of 0.08; envelope structure interior finish material settings for The walls are finished with white and beige paint (reflectance ratio 0.70), the roof is finished with cement mortar (reflectance ratio 0.32) and the floor is finished with white marble tiles (reflectance ratio 0.60).

In this simulation, the ground floor of the building was chosen as the object of analysis, and the full-sunny model was used to simulate the indoor light environment, selecting a plane at a height of 0.75 m above the ground as the natural light for the analysis. On the one hand, by simulating the weather conditions at the same time of the summer solstice (June 21st), the simulated comparative data analysis of the different wall materials of the building was carried out, and on the other hand, by simulating the comparative analysis of the building using TLAC at different points in time, using the summer solstice as the base. The ground floor plan of the villa building is shown in figure 3. The three-dimensional building model is shown in figure 4.

3. Results and discussion

3.1. Analysis of light transmittance experiment
Compared with traditional building composite materials, a TLAC is an innovative energy-saving construction material. TLAC was prepared by SCM and POFs to allow inward natural light transmission. The light transmission properties of TLAC are normally evaluated in terms of the light transmission power. In this study, the light transmission properties of TLACs in the visible wavelength band (400–1000 nm) were investigated using the optical power method.

Figure 5 shows the light transmission of TLACs at different POF volume admixtures and different wavelengths. It can be seen that the maximum transmittance of the specimens at different wavelengths was 3.20%, 3.42%, 3.68%, and 3.91% for different POF volume doping levels from 2% to 5% at a fiber diameter of 0.5 mm. Henriques et al [30] also demonstrated that the light transmission increased with increasing fiber content when the fiber content reached 5%. This is due to the increased volume doping of the fibers, which allows for more diverse light propagation paths and increased photoconductive synergy between the fibers.
It was also found that the transmittance of TLAC established an almost linear relationship with wavelength under an incandescent light source [31]. Theoretically, the transmittance of TLAC specimens should remain correlated with the POF volume doping, but it was observed that the actual test results of the transmittance of some specimens were small. On the one hand, this is due to the large light scattering angle of the incandescent lamp and the attenuation of the light transmission process in the optical fiber. Song et al. [32] demonstrated that the optical fiber attenuation rate increases with increasing angle of incidence. On the other hand, it is due to the polishing of the fiber section in place causing the access port to be obscured by the cement matrix or possible contamination of the fiber section.

In addition, the maximum transmittance of the specimen with a POF volume doping of 3.5% was 4.97% at a fiber diameter of 1 mm. It can be found that for the same number of TLAC specimens with the same number of fibers, the light transmission of the specimens doped with 1 mm diameter fibers is significantly greater than that of the specimens with 0.5 mm diameter fibers. This is due to the larger transmission area of specimens using larger diameter fibers. While Li et al. [29] also demonstrated that the optical power increased with the number of fibers and the diameter of the fibers. Overall, the imagination of permitting light through the concrete by optical fibers there will be a better interaction between the construction and its environment and diminishing the energy expenses in modern infrastructures [19].

3.2. Compressive strength of the TLACs
Figure 6 indicates the compressive strength of TLACs cured for 7 d and 28 d. It can be found that the strength increases from 7 d to 28 d for all the evaluated mixtures, this is due to the improvement in the hydration response.
of cement and the formation of a higher extent of merchandise such as hydrated-calcium-silicate gel (C–S–H) and portlandite (CH) [33]. The compressive strength values ranged from 21.825 MPa to 51.624 MPa at 28 d. In general, the compressive strength increased with increasing volume dosing fiber and then gradually decreased. When the volume admixture was below 4%, the strength increased linearly with the increase of volume admixture, and when the volume rate exceeded 4%, the compressive strength of the matrix decreased rapidly. This is because the internal fiber gap is smaller when the fiber dosage exceeds 4%, the mortar content at the unit volume decreases and the mortar is less adhesive to the fiber surface, resulting in a significant reduction of mortar strength. Moreover, the higher incorporation volume of POF failed to achieve the structural reinforcement effect due to the increasing interface areas between the cement matrix and POF. Owing to the non-absorbent nature of the POF, water films form around the POF (i.e. wall effect), thus leading to the formation of porous and brittle transition zones with the subsequent hydration of cement, which significantly decreases the strength of mortar reinforced by POF. While Li et al [29] have also shown that excessive fibers could be considered as defects in cement mortar in compressive strength tests. It can be seen that the low

![Figure 5. Transparency of TLACs with different POF volume fractions and wavelength.](image)

![Figure 6. Compressive strength of TLACs cured for 7 and 28 d.](image)
incorporation of optical fibers increases the compressive strength of the system, which first increases and then decreases with the increase in the volume of optical fibers incorporated. This is because a small amount of fiber doping will have a fiber reinforcing effect on the compressive strength of the specimen and improve the compressive strength of the specimen, but as the volume of fiber doping increases, the inhomogeneity of the matrix increases significantly, ultimately reducing the compressive strength of the specimen.

The TLAC blocks before and after the compression test are shown in figure 7. The test block was broken and the internal optical fibers were fractured. It can be judged that when the concrete is subjected to pressure loading, the internal optical fibers are bent and fractured, so the light-sensitive effect inside the test block will also change. After 28 d of curing, the compressive strength of ordinary light aggregate concrete was 57.36 MPa, while the compressive strength of TLAC made with POF was between 24.25 and 37.37 MPa. The TLAC which contains POF in the concrete shows a decrease in compressive strength when compared to normal light aggregate concrete. This is due to the influence of the smooth nature of the surface of POF, POF and composite light aggregate slurry bond are poor, the emergence of weak interface areas [19, 30]. In addition, the standard ASTM C55 specifies a minimum strength of 17.2 MPa for concrete blocks and ASTM C1634 specifies a minimum strength of 24.1 MPa for structural blocks for indoor and outdoor use [33]. Therefore, the five sets of building cube models evaluated with fiber optics were higher than the values specified in the above standards.

3.3. Analysis of simulation results

3.3.1. Light transmission analysis of different wall materials

In this study, REVIT software was used to analyze the lighting situation of the ground floor of the building. To make the simulation results more accurate and informative, the concrete blocks with a volume reference of 4% are used as the object of analysis, and different wall materials are used to simulate and compare the daylighting effect on the ground floor of the villa under normal window opening conditions. To test the prototype, the BIM model of the building was created in Revit. The sky was described as the summer solstice (21 June) and the Sun option was switched on in the Gensky project. The time for the brightness simulation was set to 12:00 PM [22].

The light transmission of the different wall materials at the same point in time is shown in figure 8. The use of light-transmitting concrete, there is a clear trend towards an increase in interior illuminance and a gradual increase in light levels at various points within the rooms on the ground floor of the building. With the use of light-transmitting concrete for the wall material, the illuminance levels increase by 24% in the ground floor bedrooms, 24% in the living room, 9% in the dining room, and 80% in the kitchen. The garage illuminance remains largely unchanged as the garage door takes up a larger portion of the building. Kota et al [22] also concluded that the Radiance model was generated by Revit2Radiance and could be visualized using the RVIEW program. The views generated by the RVIEW program match the Revit model exactly, showing the accuracy of the geometric translation. Therefore, based on the analysis of the simulation of the rooms on the ground floor, it can be seen that there is a clear trend towards an increase in illuminance in the rooms as the area used for the TLAC blocks increases.

3.3.2. Light transmission analysis at different times

Figure 9 shows the light transmission through the building at different times of day when transparent concrete has been used. A comparison of the REVIT simulation analysis shows that there is a clear trend towards increased illuminance in the room at four-time points during the day due to the use of the TLAC and that the light levels at various points in the room gradually increase as the outdoor illuminance increases. A simulation
Figure 8. False-color image showing illumination levels of building layer: The original model (a); Building models using TLAC (b).

Figure 9. False-color image of light transmission at different times of the day on the building level: 9 o’clock (a); 11 o’clock (b); 13 o’clock (c); 15 o’clock (d).
study was carried out on the ground floor of the building, using light-transmitting concrete blocks, where the illuminance values at all points in the room increased significantly from morning to midday as the solar altitude angle gradually increased. In addition, the illuminance uniformity (minimum illuminance/average illuminance) at 9, 11, 13 and 15 o’clock was 0.20, 0.13, 0.15 and 0.17 respectively. Although the illuminance values varied significantly from point to point throughout the day, the uniformity of illuminance did not vary significantly, with the smallest uniformity at midday, indicating that it is easier to increase visual fatigue. The uniformity of illuminance in the morning and afternoon is slightly improved compared to midday. The distribution of illuminance values is regular, reflecting the unevenness of natural lighting. This shows that it is difficult to achieve a reasonable lighting effect by relying on natural lighting alone in the room and must be combined with artificial lighting to achieve the desired lighting effect.

In summary, the 3D building model constructed by Revit software was used to calculate and analyze the illuminance of interior work surface points by selecting one of the floor planes as the object of study to derive a model-based natural light distribution pattern. The prototype creates luminance files directly from the Revit model with efficiency and accuracy through automated steps. Additionally, the seamless link between Revit and Radiance, integrating lighting analysis into the BIM environment, helps to make informed design decisions and can provide some data support for green building assessment, as well as providing a reference for lighting design and analysis, thus achieving savings in lighting power consumption and reducing energy consumption.

Therefore, we can conclude that the composite building materials consisting of self-compacting lightweight aggregate mortar, and pre-placed POFs, i.e. the so-called TLACs, show excellent light transmission properties, low cost, and low energy consumption in comparison with the conventional building materials. As summarized from the results above, the fiber content and diameter in the TLAC mixtures are recommended as 4% by volume and 0.5 mm, respectively, considering the compressive strength and enabling light-transmitting.

4. Conclusions

In this paper, a new type of TLAC is developed and evaluated based on the excellent light-conducting properties and elastic optical effects of optical fibers, combined with the excellent properties of self-compacting mortar. Based on the results and discussion above, the conclusions are drawn as follows:

(1) The light transmission properties of TLACs depend mainly on the volume ratio and diameter of the POFs. The light transmission of the sample increases with the number of fibers. For the same number of fibers, the TLAC specimens show higher light transmission with the incorporation of large-diameter fibers.

(2) The compressive strength of TLACs is mainly associated with the incorporation volume ratio of POFs. The compressive strength of specimens with fibers is lower than that of specimens without fibers. The compressive strength tends to increase first and then decrease with the increasing volume fraction of POF in the TLAC samples.

(3) The simulation and quantitative analysis of light transmission showed the lighting effect and energy-saving benefits, further demonstrating that the application of TLAC as a modern building material will contribute to sustainable construction.

(4) TLACs show superior cost efficiency and energy savings than conventional concrete. The optimal mixture proportions are further recommended as those with the diameter of 0.5 mm and the volume fraction of 4% considering the strength, light transmission, economic and environmental impacts of TLACs.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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