CO_2 EMISSION REDUCTION EFFICIENCY OF LIGHT TRANSMITTING CONCRETE AND INFLUENCING FACTORS

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Abstract - This study examines the potential of light-transmitting concrete (LTC) in reducing CO_2 emissions by using PMMA fibers and rods of different diameters and contents. Optical tests determined the light transmission coefficient of LTC samples to analyze CO_2 reduction efficiency per 1 m² of LTC. Results show that higher PMMA content in concrete improves light transmission, boosting energy savings and reduction of CO_2 emissions. Large-diameter PMMA rods are more efficient than small-diameter fibers. With an average annual illuminance of 50,000 lux, 1 m² of LTC containing 30% PMMA rods can reduce CO_2 emissions by 80 kg/year, nearly 10 times more effective than LTC with PMMA fibers under 1.5 mm in diameter and content below 8%. Effectiveness varies with geographic location and panel orientation relative to natural light.

Key words - Light transmitting concrete; optical test; CO_2 emission; daylighting energy; environmental impact

1. Introduction

The increasing demand for minimizing the environmental impact of the construction industry has driven the development of sustainable and environmentally friendly building materials [1]. Among these, concrete plays a particularly important role due to its high energy consumption during cement production and the extraction and processing of other raw materials. To address this issue, developing new functional properties for concrete to offset the energy consumed during production is a significant research direction, aligning with current trends.

Light-transmitting concrete (LTC) is an advanced material that combines structural load-bearing capacity, architectural aesthetics, and the potential for energy savings from an environmental perspective [2]. This material is produced by integrating transparent or translucent components, such as Polymethyl Methacrylate (PMMA) fibers or rods, or glass, into the concrete matrix. These components can be arranged in parallel [3] or randomly dispersed [4], allowing natural light to penetrate through the concrete panels. By adjusting the content of these components, LTC can be designed to transmit light intensity appropriate for the functional requirements of each space, while also offering superior thermal insulation and impact resistance compared to tempered glass or other transparent materials.

Previous studies on LTC have mainly focused on evaluating its mechanical properties [3-7], including strength, permeability, and durability, aiming to optimize the material mix for application in structural components such as walls, stairs, floors, and pavements [8]. Recent studies by the authors [9, 10] have shown that with a suitable concrete mix, LTC can contain up to 30% PMMA while maintaining a compressive strength above 40 MPa, which is suitable for most structural applications. However, the core value of LTC lies in its lighting energy-saving efficiency, thereby reducing CO_2 emissions, which has not been quantitatively assessed in most previous studies.

When used in construction, LTC can reduce the demand for artificial lighting by allowing natural light to penetrate and illuminate interior spaces, thereby reducing CO_2 emissions through lower energy consumption. These effects also depend on various design parameters of LTC, with the most important being the content and diameter of the light-transmitting materials used. In addition, other factors such as the geographic location of the LTC application area or the installation orientation of the LTC panels significantly affect this efficiency and need to be clarified to maximize the effectiveness of LTC in practical applications.

Therefore, this study aims to provide a quantitative assessment of the potential lighting energy savings and CO_2 emission reduction efficiency of LTC. First, optical experiments were conducted on LTC samples using PMMA fibers and rods of varying diameters and contents to determine the light transmission coefficient. Subsequently, the study analyzed the amount of lighting energy saved and converted this value into CO_2 emission reduction efficiency per 1 m² of LTC panel. Influencing factors, including the illuminance of natural light, the CO_2 emission factor of the area where LTC is used, and the panel orientation relative to incident light, are also analyzed in detail in this research.

2. Optical experiments

2.1. Sample preparation and experimental setup

LTC consists of two main components: the concrete matrix and the transparent material responsible for light transmission. The concrete matrix serves as the structural framework of LTC, while the transparent material is integrated into the matrix to transmit light, creating both aesthetic effects and lighting efficiency for the structure. In this study, PMMA plastic was used in the form of fibers with diameters less than 2.0 mm and rods with diameters greater than 10 mm. PMMA was selected due to its near-complete light transmittance, excellent workability for fabrication, and high durability against environmental impacts.

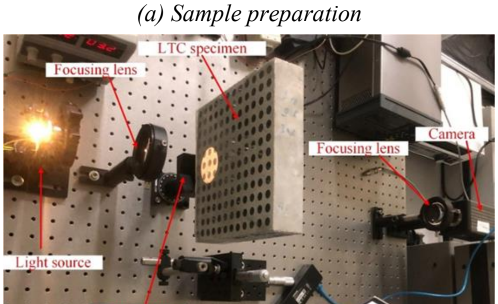
In principle, enhancing the light transmission capability of LTC requires increasing the volumetric content of transparent PMMA within the concrete. However, significantly increasing the PMMA content raises the demand for workability so that the concrete mix can flow into the narrow gaps between the PMMA fibers, and may also reduce the mechanical strength of LTC due to the reduced load-bearing concrete matrix volume displaced by PMMA. Therefore, the design of the concrete mix must balance sufficient workability to fill the narrow spaces between PMMA fibers or rods, while maintaining high design strength to meet the requirements for use in load-bearing components.

Based on these considerations, this study employed a concrete matrix mix designed according to the principles of ultra-high performance concrete, consisting of cement, fine mineral powders such as ground granulated blast furnace slag and fly ash, fine sand, water, and superplasticizer. The detailed mix design has been presented in the authors' previous publications [9, 10]. As this study focuses on evaluating the light transmission capability of LTC and its environmental impact, only the proportions of the concrete matrix mix are shown in Table 1, without detailing the properties of the raw materials.

Table 1. *Mixture proportion of concrete mixture (kg/m^3)*

Fine sand	Cement	Blast furnace slag	Fly ash	Superplasticizer	Water
1183	495	270	135	6.3	240

(a) Sample preparation



(b) Optical test method

Figure 1. *Experiment preparation*

The formwork used to shape LTC samples is illustrated in the upper part of Figure 1(a). In this study, four types of PMMA fibers with diameters of 0.75 mm, 1 mm, 1.5 mm, and 2.0 mm, as well as two types of PMMA rods with diameters of 10 mm and 15 mm, were used. At the same volumetric content, smaller diameter fibers result in smaller spacing between fibers. For this reason, for PMMA fibers with diameters less than 1.5 mm, producing LTC with fiber content above 10% is not feasible, as the spacing between fibers becomes too small (less than 2.0 mm). Therefore, for these small-diameter PMMA fibers, the maximum volumetric content applied was below 7.1%. In the case of 2.0 mm diameter PMMA fibers, the volumetric content could reach 10% and 20%, corresponding to fiber spacings of 4.4 mm and 3.6 mm, respectively. For PMMA rods with diameters greater than 10 mm, three volumetric content levels were applied: 10%, 20%, and 30%, with the spacing between rods always greater than 5 mm in all cases.

The formwork was removed 48 hours after casting. Some test samples, shown in the lower part of Figure 1(a), exhibited smooth surfaces without voids or defects. This demonstrates that the concrete mix design was suitable for producing LTC samples with high PMMA volumetric content.

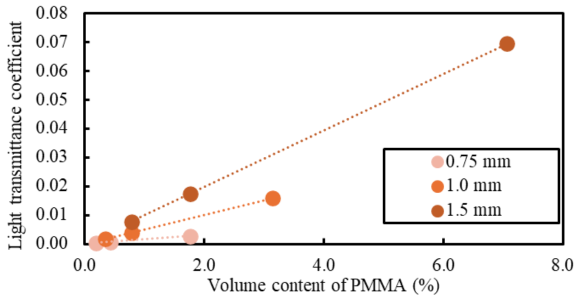
The optical experimental setup for LTC samples is shown in Figure 1(b). An Ocean Insight UV-NIR USB 2000+ spectrometer was used to analyze the spectral characteristics of light transmitted through LTC from a visible light source. The LTC samples, all with a thickness of 40 mm and a side length of 200 mm, were placed directly in front of the light source. The distance of the light source was adjusted so that the focal plane of the light beam coincided with the plane of the LTC sample. The light transmission coefficient was determined as the ratio of the intensity of light transmitted through the sample to that of the incident light.

2.2. Experimental Results

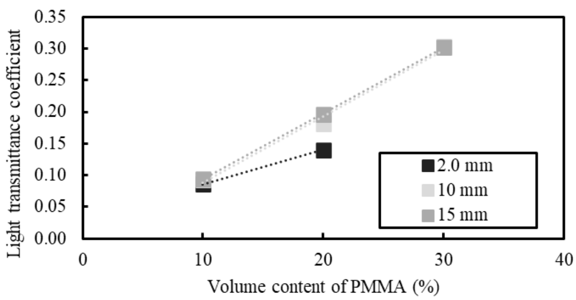
The mechanical properties of the LTC samples used in this study, corresponding to different PMMA contents, have been analyzed in the authors' previous studies [9, 10]. The flowability of the concrete matrix exceeded 18 cm, and the compressive strength of LTC was above 40 MPa in all cases, regardless of PMMA content. Detailed analyses can be found in the published studies [9, 10].

The relationship between the light transmission coefficient and the volumetric content of PMMA in LTC is presented in Figures 2(a) and 2(b). The data in the charts are color-coded to distinguish the diameters of the PMMA fibers or rods used in LTC.

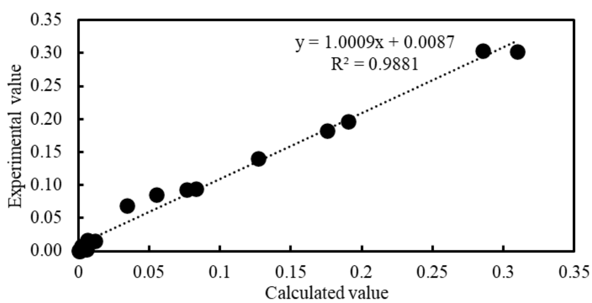
Experimental results indicate that the light transmission coefficient of LTC samples increases almost linearly with increasing PMMA volumetric content in the concrete mix. However, the rate of increase is not uniform and depends on the diameter of the PMMA fibers or rods. Specifically, when the PMMA volumetric content reaches about 2–3%, the transmission coefficient of samples using small-diameter PMMA fibers (0.75 mm and 1.0 mm) remains below 0.02. In contrast, for PMMA rods with diameters greater than 10 mm, the transmission coefficient is nearly equivalent to the volumetric ratio of PMMA in the concrete. Thus, the slope of the relationship between the transmission coefficient and PMMA volumetric content tends to be higher for larger-diameter PMMA fibers or rods. The main reason is that when smaller-diameter PMMA fibers or rods are used, light is more strongly scattered during transmission through the concrete, resulting in decreased transmitted light intensity. This has been demonstrated in several previous studies [10, 11].



(a) LTC with PMMA diameter below 1.5 mm



(b) LTC with PMMA diameter larger than 2.0 mm



(c) Relationship between calculated and experimental light transmittance coefficients

Figure 2. *Results of Light transmittance coefficient of LTC*

From the above analysis, it can be seen that the light transmission coefficient is affected not only by the volumetric content of PMMA but also significantly by the diameter of the PMMA material used. To accurately evaluate this relationship, the study conducted a multivariate regression analysis to determine the dependence of the light transmission coefficient of LTC samples (C^{LTC}) on independent variables including volumetric content (V_f) and diameter (D) of the PMMA used. The results show that the relationship among these variables can be expressed by Equation (1) below:

$$C^{LTC} = 3.0 \times 10^{-3} \times V_f^{1.2} D^{0.2} \quad (1)$$

Figure 2(c) presents a comparison between the experimentally obtained light transmission coefficients and the values calculated using Equation (1). The regression line has a slope of approximately 1.0 and a coefficient of determination greater than 0.98, indicating a high correlation between the calculated and experimental data. This demonstrates that Equation (1) can be used to predict the light transmission coefficient when varying the volumetric content and diameter of PMMA in LTC samples.

3. Calculation method for lighting energy savings and CO_2 emission reduction

To calculate the energy-saving efficiency from natural lighting provided by LTC, it is first necessary to determine the illuminance of sunlight that can reach the LTC panels when used as exterior wall material in buildings. Illuminance of natural light is measured in lux (lx), representing the amount of light per unit area (1 lx = 1 lm/m²), where lumen (lm) is the SI unit of luminous flux, measuring the total amount of visible light emitted by a source per second in all directions.

The total annual illuminance of natural light can be determined using a double integral [12], which accumulates the total daily illuminance and then sums this value over all days in a year, expressed as follows:

$$I_{year} = \int_{d=1}^{365} \int_{t1}^{t2} I(t,d)\, dt\, dd \quad (2)$$

Here, I_{year} (in lx×h) is the total annual illuminance, and I(t,d) can be expressed as a cosine function to represent the variation of illuminance over the course of a day [13]:

$$I(t,d) = I_{max}(d) cos\left(\frac{\pi}{T_d}(t - t_{noon})\right) \quad (3)$$

Where, $I_{max}(d)$ is the maximum daily illuminance, T_d is the number of sunlight hours in a day, and t_{noon} the time of peak illuminance. Assuming 12 hours of daylight (from 6 a.m. to 6 p.m.) and peak illuminance at noon, equation (2) can be rewritten as:

$$I_{year} = \int_{d=1}^{365} \int_{6}^{18} I_{max}(d) cos\left(\frac{\pi}{12}(t - 12)\right) dt\, dd$$
$$= \int_{d=1}^{365} 7{,}65 I_{max}(d)\, dd = 2792 I_{ave(\max)} \quad (4)$$

Where, $I_{ave(\max)}$ is the average daily maximum illuminance at the location, averaged over the year. This value varies depending on geographic location.

Assuming the light transmission capacity of LTC is only effective within a wide incident angle range of γ degrees, and the sun's angle changes by 15 degrees per hour [9], the proportion of effective sunlight hours on the LTC panel to total sunlight hours per day is $\frac{\gamma}{15 \times 12} = \frac{\gamma}{180}$. Therefore, the total useful annual illuminance on the LTC panel can be rewritten as:

$$I_{year}^{LTC} = \frac{2792}{180} \gamma I_{ave(\max)} = 15{,}5 \gamma I_{ave(\max)} \quad (5)$$

Based on the optical experiments in Section 2, the light transmission coefficient per square meter of LTC can be evaluated as a function of design parameters, including PMMA content and diameter, using equation (1). Thus, the annual transmitted lighting energy through LTC is calculated as:

$$E_{year}^{LTC} = AC^{LTC}I_{year}^{LTC} = 0.0465AV_f^{1.2}D^{0.2}\gamma I_{ave(\max)} \quad (6)$$

Where: E_{year}^{LTC} is the annual lighting energy transmitted through LTC (in lm×h), is the illuminated surface area of LTC (m²).

Assuming the building is illuminated by artificial light sources with an efficiency η (lm/kW), and EF_i is the CO_2 emission factor (kg CO_2/kWh) based on the energy source, the annual CO_2 emission reduction from lighting energy savings via LTC can be calculated as:

$$M_{CO_2} = \frac{E_{year}^{LTC}}{\eta}EF_i = \frac{0.0465AV_f^{1.2}D^{0.2}\gamma I_{ave(\max)}}{\eta}EF_i \quad (7)$$

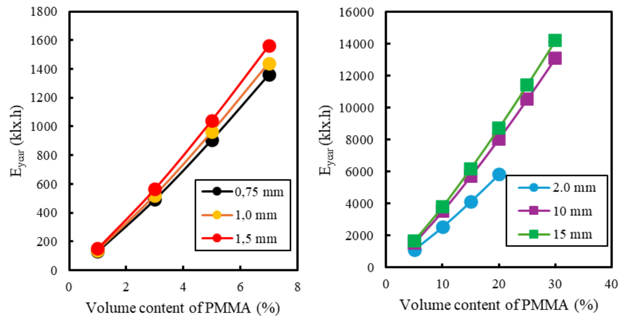
Thus, to calculate the annual natural lighting energy transmitted through LTC (equation 6) and the corresponding CO_2 emission reduction (equation 7), reasonable assumptions must be made for the coefficients A, V_f, D, γ, $I_{ave(\max)}$, η, and EF_i. Among these, V_f and D can be based on the LTC panel design parameters, and area A can be set to 1 m² for analysis per square meter of LTC. The artificial lighting efficiency (η) can be taken as the average value for LEDs, 10^5 lm/kW [14]. The remaining parameters depend on complex conditions in LTC applications; therefore, in this study, γ, $I_{ave(\max)}$, and EF_i are considered as influencing factors to evaluate LTC effectiveness under different usage scenarios.

4. Results and discussion

4.1. Effect of PMMA content and diameter

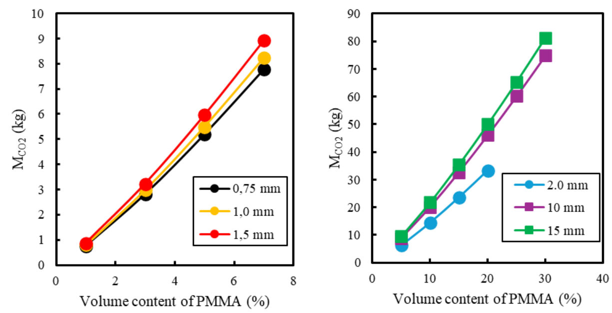
Typically, in equatorial regions, the maximum natural illuminance at noon during summer can reach up to 100,000 lux, while this value drops to about 20,000–50,000 lux in winter [9]. Therefore, in this section, the average annual maximum illuminance is assumed to be 50,000 lux, and this value will be varied in subsequent sections. The emission factor (EFi), representing the CO_2 emission per kWh of electricity generation, depends on the energy source-thermal, hydro, or renewables. In this study, based on Energy Institute - Statistical Review of World Energy [15], the average emission factor for Asia in 2023 is chosen as 0.571 kg/kWh. Additionally, the effective incident light angle range (γ) depends on the installation position of the LTC panel relative to the sun's angle, which is complex and requires specific architectural solutions. For this section, γ = 600 is used. The influence of these assumed parameters will be further analyzed later.

With these assumptions, Figure 3 shows the calculated annual transmitted lighting energy through LTC, while Figure 4 presents the annual CO_2 emission reduction due to this energy saving. Results indicate that higher PMMA content in LTC increases the transmitted lighting energy and thus the amount of CO_2 emission reduction. Notably, this effect differs among LTC samples with the same PMMA content but different diameters; samples with larger PMMA diameters yield higher transmitted energy and CO_2 reduction. This is due to the increased light transmission coefficient with larger PMMA diameters, as indicated in Equation (1).



(a) LTC with PMMA diameter below 1.5 mm *(b) LTC with PMMA diameter larger than 2.0 mm*

***Figure 3.** Lighting energy of 1m² LTC per year*



(a) LTC with PMMA diameter below 1.5 mm *(b) LTC with PMMA diameter larger than 2.0 mm*

***Figure 4.** CO_2 emission reduction amount of 1m2 LTC per year*

Figure 4(a) shows that using LTC with PMMA fiber content below 7% results in a CO_2 reduction of less than 10 kg per year per m². In contrast, Figure 4(b) shows that this value exceeds 80 kg CO_2 per year when using LTC with PMMA rods over 10 mm in diameter and 30% volume fraction. This is highly encouraging, as LTC primarily functions as wall or load-bearing components in construction, while also providing significant light transmission and emission reduction benefits.

4.2. Effect of average maximum illuminance

The calculations in Section 4.1 are based on an assumed annual average maximum illuminance of 50,000 lx. However, this value depends on the geographic location of the building using LTC. In equatorial regions with high solar intensity and long daylight hours (e.g., Southeast Asia, Africa, South America), the average maximum illuminance can be much higher than 50,000 lx. Conversely, in high-latitude areas such as Northern Europe or North America, especially in winter, it can be significantly lower. Environmental factors like tall buildings, trees, or mountainous terrain can also affect local maximum illuminance. Figure 5 shows the calculated CO_2 emission reduction as the average maximum illuminance varies from 10,000 to 100,000 lx for three LTC samples: 1.0 mm fiber at 7% content, 2.0 mm fiber at 20% content, and 15 mm rod at 30% content.

Results show that as average maximum illuminance increases, CO_2 emission reduction increases significantly for all three samples. Specifically, for each m² of LTC with 1.0 mm fibers, emission reduction rises from about 2 kg at 10,000 lx to 30 kg at 100,000 lx per year. Similarly, LTC with 2.0 mm fibers at 20% content increases from about 10 kg to 100 kg, and the 15 mm rod sample at 30% content increases from 20 kg to 160 kg per year.

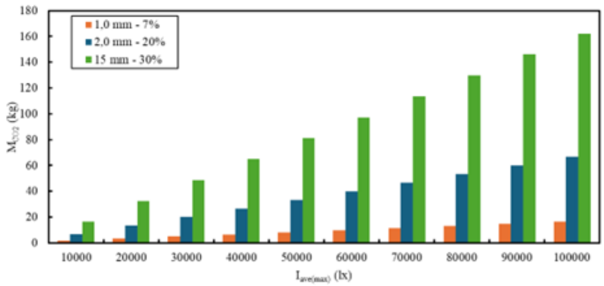


Figure 5. *Effect of average maximum illuminance on CO_2 emission reduction amount per year*

At the same maximum illuminance of 100,000 lx, the LTC sample with 15 mm rods at 30% content achieves an emission reduction five times higher than the 1.0 mm fiber sample, and about 1.6 times higher than the 2.0 mm fiber sample at 20% content. This demonstrates that LTC with larger diameter rods and higher content offers superior lighting energy savings and significant CO_2 emission reduction, especially under high natural lighting conditions.

4.3. Effect of country-specific CO_2 emission factors

Figure 6 shows the impact of country-specific CO_2 emission factors on annual emission reduction for the same three LTC samples as in Section 4.2. Since the emission factor (EF) is the amount of CO_2 emitted per unit of energy produced (kg CO_2/kWh), it depends on the country's energy mix. Fossil fuel sources like coal, oil, and natural gas have high emission factors, while renewables like hydro, wind, and solar have near-zero emission factors. Thus, a country's emission factor depends greatly on its energy structure.

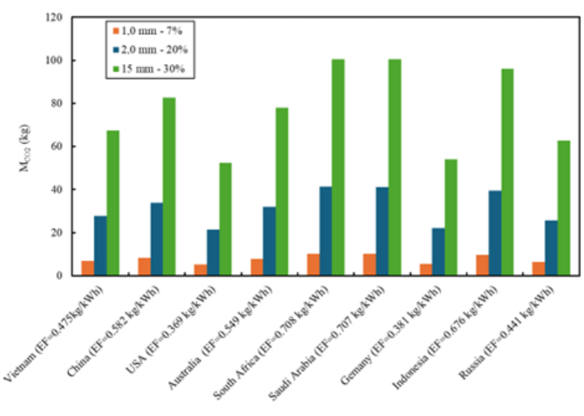


Figure 6. *Effect of CO2 Emission Factors by Country on CO_2 emission reduction amount per year*

In this study, based on Energy Institute data [15], the considered countries and their EFs are: Vietnam (0.745 kg/kWh), China (0.674), USA (0.509), Australia (0.549), South Africa (0.790), Saudi Arabia (0.779), Germany (0.376), Indonesia (0.716), and Russia (0.441). South Africa and Saudi Arabia have the highest EFs (0.790 and 0.779 kg/kWh) due to heavy reliance on coal and oil, while Germany has the lowest (0.376 kg/kWh) due to a high share of renewables.

Calculations show that CO_2 emission reduction depends significantly on a country's emission factor. For example, with the 15 mm rod, 30% content LTC sample, CO_2 reduction in South Africa reaches about 120 kg/year, 2.5 times higher than in Germany (about 45 kg/year). Similarly, the 2.0 mm, 20% fiber sample achieves about 80 kg/year in South Africa, but only about 30 kg/year in Germany; the 1.0 mm, 7% fiber sample ranges from about 5 kg/year (Germany) to 20 kg/year (South Africa).

This demonstrates that using larger diameter, higher content PMMA rods in LTC offers outstanding CO_2 emission reduction, especially in countries with high emission factors and heavy fossil fuel use.

4.4. Effect of useful incident light angle range

Figure 7 shows the impact of the useful incident light angle range (γ) on annual CO_2 emission reduction for LTC panels. γ is defined as the angle range within which light can pass through LTC without changing the transmission coefficient.

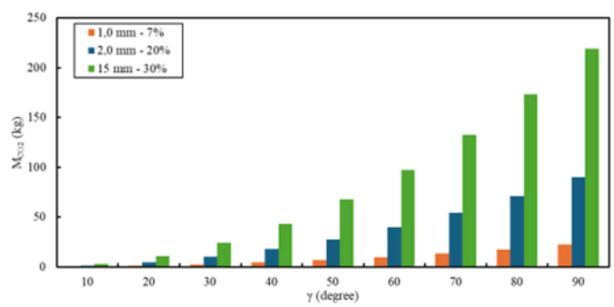


Figure 7. *Impact of light effective angle range on CO_2 emission reduction amount per year*

Results indicate that as γ increases from 0° to 90°, CO_2 emission reduction increases significantly for all materials, but the degree of increase varies. Each m^2 of LTC with 15 mm rods at 30% content achieves the highest reduction, rising from about 20 kg at $\gamma = 10°$ to nearly 240 kg at $\gamma = 90°$. The 2.0 mm, 20% fiber sample also rises significantly, from 10 kg to 120 kg over the same γ range. Although the 1.0 mm, 7% fiber sample has the lowest reduction, it still increases sharply with γ, from about 2 kg at $\gamma = 10°$ to 40 kg at $\gamma = 90°$, a 20-fold increase. This shows that even LTC with small diameter, low content fibers can achieve significant emission reductions when the useful incident light angle range is expanded.

The results highlight that the placement of LTC panels in a building not only affects architectural effects but also greatly impacts the material's CO_2 emission reduction effectiveness. For example, LTC panels installed on vertical facades often have limited γ, especially during times of day when sunlight is horizontal. In contrast, LTC used in roofs or skylights can receive light over a wider angle range, enhancing CO_2 reduction effectiveness.

5. Conclusion

This study fabricated LTC using PMMA fibers and rods with varying contents and diameters, and conducted optical experiments to evaluate their light transmission coefficients. Additionally, the research calculated the CO_2

emissions from LTC production and the CO_2 emission reduction achieved through lighting energy savings when using this material. The main findings are as follows:

(1) The light transmission coefficient of LTC depends not only on the PMMA volume fraction but also on its diameter. Larger diameters yield higher transmission coefficients, and this relationship can be expressed as a nonlinear function.

(2) Increasing the PMMA content enhances light transmission efficiency, thereby increasing CO_2 emission reduction. PMMA rods with larger diameters provide better emission reduction than smaller fibers.

(3) In regions with an average maximum illuminance of about 50,000 lx, each square meter of LTC panel using PMMA fibers with diameters less than 1.5 mm and content below 7% achieves a CO_2 reduction of less than 10 kg per year from lighting energy savings. In contrast, this value exceeds 80 kg CO_2 when LTC with PMMA rods larger than 10 mm in diameter and 30% volume fraction is used.

(4) LTC achieves greater environmental impact when applied in areas with high natural illuminance and in countries heavily reliant on fossil fuels with high CO_2 emission factors. Each square meter of LTC panel using PMMA rods at 30% content can reduce up to 160 kg of CO_2 per year in regions with an average annual maximum illuminance of 100,000 lux.

(5) Architectural design that enables LTC panels to receive useful incident light over a wide angle range significantly increases emission reduction effectiveness.

While this study mainly focused on the usage phase and lighting efficiency, future research should integrate emissions from raw material production, LTC fabrication, and construction processes to fully assess net emissions over the entire life cycle of the material. This will allow calculation of the payback period required for CO_2 savings during LTC use to offset initial emissions from production and construction. To perform such analyses accurately, it is essential to refine production technology, construction methods, and clearly define practical application conditions in subsequent research phases.

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