International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 2 (2018) pp. 1209-1218

Experimental Evaluation on Light Transmittance Performance of Translucent Concrete

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Abstract

Translucent concrete is a new energy-saving building material that permits transmission of light into indoor environment because of the embedded optical fibers with application as architectural wall and structural façade of buildings. In this experimental study, the light transmittance performance of plastic optical fiber (POF) based translucent concrete was evaluated using an electrical circuit test setup with light dependent resistor (LDR). A total of 18 specimens containing 2 mm and 3 mm fiber diameters and POF volume ratio of 2%, 4% and 6% were produced. The experimental results showed that the light transmission increased with the increases of POF volume ratio. On the other hand, the amount of light transmitted gradually decreased with the increase in distance between the specimen and light source. Moreover, the intensity of light transmitted through translucent concrete gradually decreases with respect to increases in distance between LDR and specimen. The spacing, diameter and number of optical fibers have a considerable effects on the overall ratio of light transmitted. Empirical curves are developed based on correlation between light transmittance and other various factors that affect the efficiency of light transmission through translucent concrete. The translucent concrete prepared in this study performs up to 22% of light transmittance, which is sufficient illuminance for residential and office buildings. The results evidently show that translucent concrete can be successfully used as energy efficient construction material for sustainable construction and green building development.

Keywords: translucent concrete, light transmittance, plastic optical fiber, light dependent resistor, sustainable construction, green buildings

INTRODUCTION

Energy conservation is a key and emerging global issue for sustainable infrastructure development. The building sector energy demand accounts approximately 34% of the world's energy demand [1]. Artificial lighting consumes around 19% of the total delivered electricity, worldwide [2]. The electric lighting demand has constantly been increasing with the increase in the population, urbanization and construction of high-rise buildings. The production of electricity contributes to the increase in the greenhouse gas emissions. According to EIA [3] report, the total CO_2 emission related to lighting was approximately 7% of the total global CO_2 emission in 2005. A lot of efforts have been made to reduce the energy consumption of lighting by fabrication of energy efficient lighting equipment's, improving lighting designs and using lighting control systems. Translucent concrete is an innovative solution towards significantly reducing the need for artificial lighting. This in turn reduces the carbon footprint by allowing transmission of natural light into building's interior when the translucent concrete is used as structural façades and architectural walls, thus fostering the development of green buildings.

Natural light is a form of energy reflected as electromagnetic wave that contains full spectrum of the sunlight, which is healthy for human beings and a preference than artificial light [4]. Indoor environments with adequate natural light illumination have been proven to decrease stress of occupant, improve visual comfort and render better employee retention [5]. It is then essential to develop a new type of construction material, which can allow transmittance of appropriate luminance level of natural light into buildings and integrate the concept of green energy saving [6].

The density and opacity nature of concrete ingredients hinders the transmission of light and consequently results in opaqueness of the material. However, concrete could be transformed from opaque to translucent by integrating optical fibers with a concrete matrix. Translucent concrete is a new energy-saving building material that permits transmission of light into indoor environment through the embedded optical fibers. Besides light transmittance, translucent concrete is able to show the silhouettes of any proximal objects situated on the brighter side of the wall, thereby, it can also be used for application in architecture of prison, bank and museum to ensure safety and security [7].

Translucent concrete can be produced in an even distribution and parallel spatial pattern arrangement of plastic optical fibers embedded with self-compacting mortar or fine concrete matrix. The light transmittance properties rely on the volume ratio and numerical aperture of optical fibers incorporated. Plastic optical fiber (POF) is an optical fiber made of poly methyl methacrylate (PMMA) core and fluororesin cladding materials with more than 96% of the cross-section able to transmit light effectively. The structural components of optical fiber consist of three layers: core, cladding and buffer coating. However, fibers used in translucent concrete should not have buffer coating to reinforce the interfacial bondage between the concrete matrix and fiber surface. The refractive index profile of POF core can be step-index or graded-index depending on the mode of total internal reflection, while the cladding index is uniform to keep the propagation of the discrete path of light rays within the core [8–10]. The mechanism of light transmittance through optical fibers is free of light-heat, photochemical and photo elastic effects.

Cement based translucent concrete is a combination of a conventional concrete components such as cement, fine aggregate and water, and around 2% - 6% of optical fiber by percentage of the total specimen volume. Load bearing and non-load bearing translucent concrete panels or façades should fulfill the strength, serviceability and durability requirements to withstand expected ultimate loads with permissible deflection [11]. Furthermore, the light transmittance performance should be enough to meet the minimum illuminance level for optical activity of people in indoor environments and comply with standards such as the Australian/New Zealand Standard [12]. The intensity of light is usually measured using instruments such as light meter, optical power meter, lux meter and luminous photometer. The light can also be measured using electrical circuit setup with light dependent resistor in a laboratory.

A few previous studies have been reported on the light transmittance properties of optical fiber based translucent concrete. Li et al. [13] reported that the optical power of the transmitted light gradually decreased as the distance between the specimen and light source increased. Test results show that regardless of red or white light, the optical power increases with the increase in number of fibers integrated. Uneven and irregular section of fibers on the concrete surface affects the propagation of light waves which consequently decreases the wavelength of lights transmitted through the specimen. Momin et al. [14] investigated the comparative light transmission properties of concrete embedded with glass rods and optical fibers. It is observed that, for the same spacing, the light guiding efficiency of optical fiber is much higher than glass rod. The ratio of light transmitted obtained was ranging 0.25% - 1.5% and 7.4% - 9.5% using glass rod and optical fiber respectively. Li, Li and Guo [15] observed that the fiber diameters and volume fraction as well as the thickness and the degree of surface toughness of sulfoaluminate cement-based specimens affects the amount of light transmitted. Moreover, different curing conditions such as water bath at 80 ºC significantly reduced the light transmitted through the specimens. Zhou et al. [16] examined the transmitting performance of smart epoxy resin concrete blocks using Fiber Bragg Grating (FBG) and POF for application in civil infrastructure and structural health monitoring (SHM). The optical power meter test results show that at a range of 400 - 775 nm wavelength, transmittance ratio varies 1% - 2.5% corresponding to POF area ratio of 3.14% - 5.3%. Incorporation of POF could yield a steady transmittance ratio for both visible and infrared ray lights. Altlomate et al. [17] deduced that the transmission of light through light transmitting concrete completely depends on the surface area of POF used. The authors found a maximum luminance of 75.53 LUX transmitted through the cubic specimen containing 1.43% of 1.5 mm diameter fibers, which is above the minimum standard lux level for architectural applications on corridors, passageways and indoor storage tanks according to Australian/New Zealand Standard [12].

Previous studies demonstrate the light transmittance of translucent concrete using optical fiber of less than 1.5 mm diameters. In addition, extensive studies on light transmittance performance of translucent concrete are still very rare. The aim of this experimental study is to evaluate the light transmittance performance of translucent concrete containing optical fiber diameters of 2 mm and 3 mm using light dependent resistor (LDR) for application in building construction and structural façades.

MATERIALS AND METHODS

Materials

In this study, the translucent concrete specimens were produced using self-compacting mortar (SCM) by embedding plastic optical fibers (POF). Ordinary Portland cement 42.5N type-I, limestone powder, natural fine aggregate, recycled glass aggregate, water, Sika ViscoCrete-3088 superplasticiser and POF were used to produce the translucent concrete. The optical fibers used were made of poly methyl methacrylate (PMMA) with outer diameter of 2 mm and 3 mm. The cladding material of the optical fiber was fluororesin. The core refractive index and numerical aperture of the fiber were 1.49% and 0.5 respectively. The effective bending radius was ten times greater than the diameter of the fiber and its operating temperature ranges -40ºC ~ +70ºC. The fiber was non-conductive and, its refractive index profile was step index. At 650 nm wavelength, the white light transmittance loss rate of the fiber was less than 350 dB/km. The specification of POF are given in Table 1.

Table 1: Specification of the plastic optical fibers (POF)

Description	Property
Numerical Aperture	0.5
Core material	Poly methyl methacrylate (PMMA)
Cladding material	Fluororesin
Outer diameter (Ø)	2 mm and 3 mm
Appearance/color	Transparent, smooth
Refractive index profile	Step-index
Core refractive index (%)	1.49
Heat transfer	No
Conductivity	No
Outer jacket	No
Working temperature range	-40 ºC ~ +70 ºC
Allowable bending radius	≥10*Ø
Elongation rate	≥4

Preparation of translucent concrete

The self-compacting mortar used in the production of translucent concrete was designed and evaluated based on Japanese Mix Design Method [18] and EFNARC [19], respectively. A total of 18 cubic specimens of dimension 50x50x50 mm^3 were prepared with POF diameters of 2 mm and 3 mm, and with different POF volume ratios of 2%, 4% and 6% to evaluate the light transmittance of translucent concrete. The number and spacing of POF used in the cubic specimens are shown in Table 2. Plywood and low-density polyethylene (LDPE) sheet were used to fabricate a formwork. The preparation of formwork for translucent concrete is shown in Fig. 1. The LDPE sheets were properly striped according to the required spacing, and drilled using 2 mm and 3 mm metal needle to fit 2 mm and 3 mm fiber diameters respectively. Then the fibers were woven into the drilled LDPE sheets in parallel orientation and uniform distribution. The LDPE sheets then carefully inserted into the prepared plywood formwork and the proportioned self-compacting mortar was poured into the formwork without applying any external mechanical vibration. After 24 hours, the LDPE sheets and plywood were removed carefully, and the projected fibers were cut-off using pliers. Finally, the specimens were cured in water at 20 ± 2 ºC temperature until the age of testing.

Table 2: Number of POF incorporated in to the cubic specimens for light transmittance test

Ø2 mm POF			**Ø3 mm POF**		
POF Volume (%)	No. of POF	Spacing (mm)	POF Volume (%)	No. of POF	Spacing (mm)
2	16	10	2	7	12.5
4	32	7.1	4	14	10
6	48	6.2	6	21	8.3

(a) Fixation of POF in low-density polyethylene (LDPE) sheets

(b) Preparation of cubic mould after fixing POF

Figure 1: Details of POF fixation and cubic mould preparation for translucent concrete productions

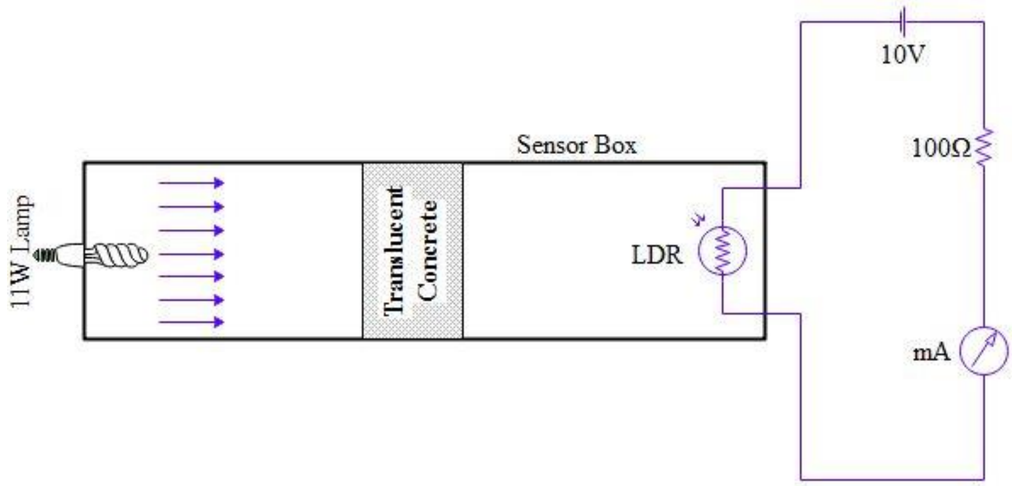


Figure 2: Schematic diagram of circuit setup for light transmittance test

Experimental setup of light transmittance test

The light transmittance performance of translucent concrete was investigated by measuring the current corresponding to the light intensity that transmitted through the specimens using an electrical circuit setup with light dependent resistor (LDR). LDR also known as photo resistor is a light sensitive resistor whose resistance varies with the wavelength of the light. For this study, a sensor box with an inside dimension of 50x50x1300 mm^3 was prepared using plywood. The translucent concrete specimens were situated at the center of the sensor box and 11 W lamp was applied at varying distance of 100, 200, 300 and 400 mm. The lamp and LDR were situated in front and behind of the specimens inside the sensor box respectively. A uniform DC voltage of 10 V was kept between the circuits and 100 Ω resistance was applied in the circuit setup. Fig. 2 and Fig. 3 shows the schematic diagram of circuit set-up and experimental arrangement of light transmittance test respectively.

Figure 3: Experimental setup and arrangement of light transmittance test

The light transmittance test of all specimens was conducted after 28 days of curing. The light transmittance efficiency of translucent concrete was measured at distance of 100, 200, 300, 400 and 500 mm from the specimen location. Fig. 4 demonstrates the illumination of typical translucent concrete prepared in this study. The percentage of light transmitted through translucent concrete specimen is calculated using a relationship given in equation (1).

$$LT(\%) = \left[1 - \left(\frac{A_1 - A_2}{A_1}\right)\right] * 100 \quad (1)$$

Where: LT refers to light transmittance, A_1 is the reference current of the light intensity of the lighting source (mA) and A_2 is the current of the light intensity transmitted through translucent concrete specimen (mA).

(a) Typical translucent concrete (Ø2 mm, 6% POF)

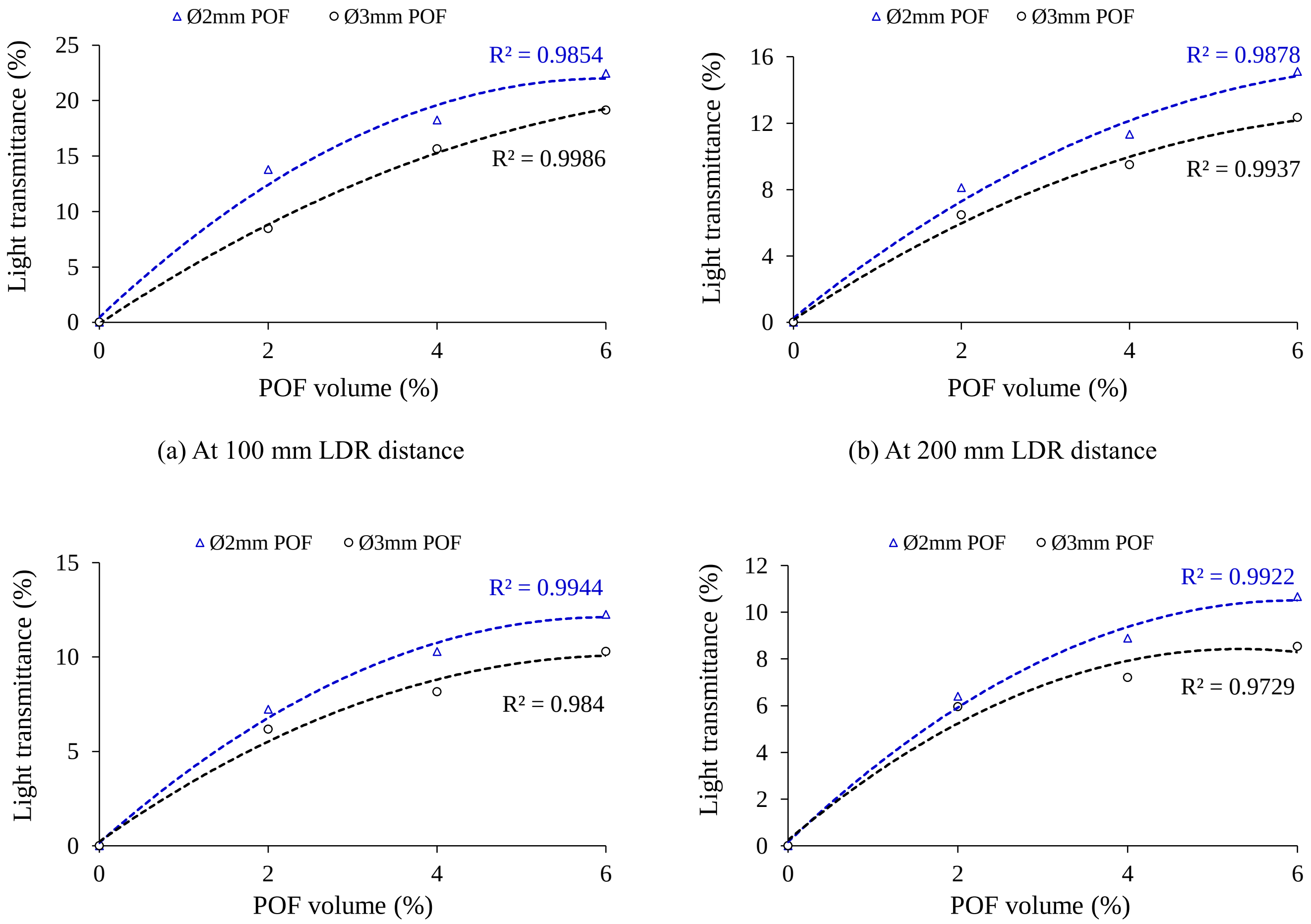
(b) Translucent concrete and LT testing equipment's

Figure 4: Translucent concrete illumination

RESULTS AND DISCUSSION

Light transmittance analysis of translucent concrete

The light transmission through translucent concrete is dependent on the percentage volume of optical fibers incorporated and the roughness degree of the surface area. Fig. 5 (a), (b), (c) and (d) graphically presents the light transmittance efficiency of translucent concrete at 100 mm distance of the light source and different LDR distances. Furthermore, the measured transmittance of the specimens at 200 mm distance of light source are presented in Fig. 6 (a), (b), (c) and (d). The amount of light transmitted was increased as the volume fraction of POF increased regardless of the diameter of fibers. This result is concurred with the findings of Altlomate et al. [17] and Zhou et al. [16], who reported that the ratio of transmittance increased with an increased percentage volume fraction of optical fibers. This is due to the fact that as the volume fraction of POF increased, the number of POF also increased and consequently increased the amount of light transmitted through the concrete. The relationship between optical fibers volume ratio and transmittance showed strong correlation ($R^2 \geq 0.95$) in quadratic trendline form. This result is in contrary with those of Paul and Dutta [20], who reported that POF volume ratio and transmittance ratio have a linear relationship. The authors' used Optical Power Meter of wavelength 400 – 1100 nm to measure the light transmittance and the test was performed on chosen middle part of the concrete surface considering small number of POF. The contrary result may be attributed to the difference in experimental methodology and testing apparatus employed.The maximum transmittance obtained was 22.44% (average of three measurements) for specimens incorporating 6% volume of 2 mm diameter optical fibers that observed at 100 mm distance of both light source and LDR from the specimen location. Whereas, the lowest transmittance was 3.68% for specimens containing 2% volume of 3 mm diameter of optical fibers measured at 400 mm and 500 mm distances of light source and LDR respectively. Therefore, the percentage volume of POF incorporated in translucent concrete remarkably influences the transmittance property.



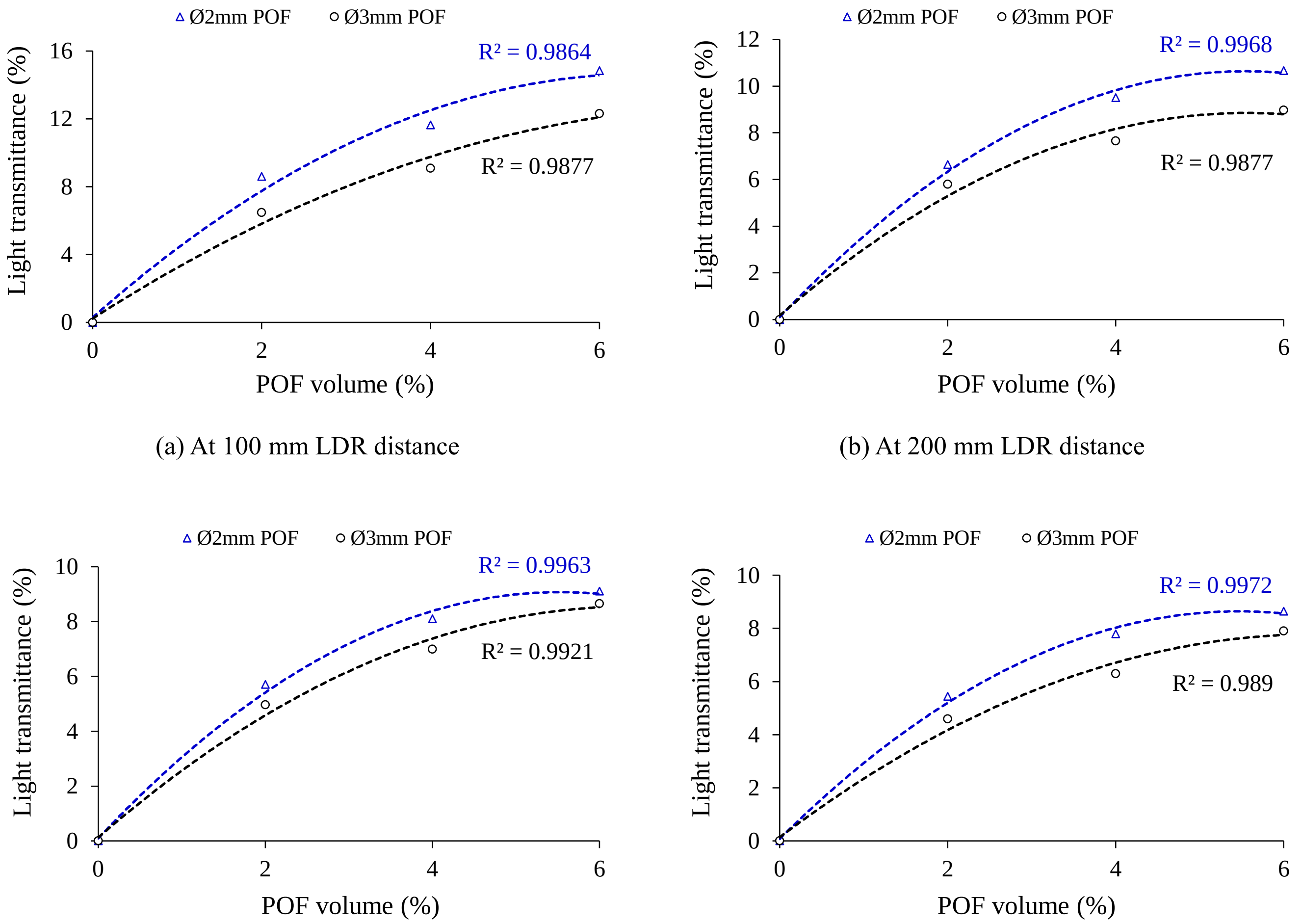
(a) At 100 mm LDR distance

(b) At 200 mm LDR distance

(c) At 300 mm LDR distance

(d) At 400 mm LDR distance

Figure 5: Light transmittance of translucent concrete (at 100 mm distance of light source)



(a) At 100 mm LDR distance

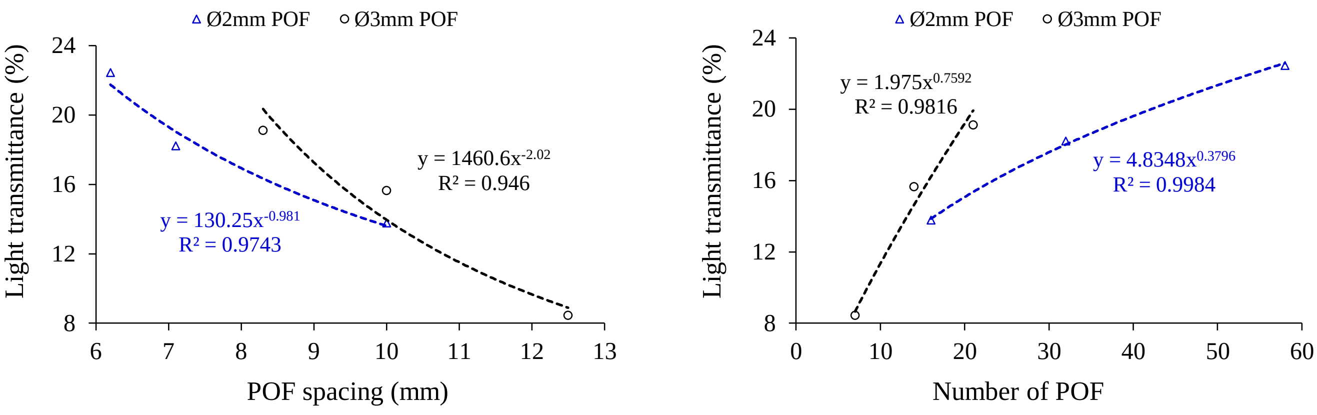
(b) At 200 mm LDR distance

(c) At 300 mm LDR distance

(d) At 400 mm LDR distance

Figure 6: Light transmittance of translucent concrete (at 200 mm distance of light source)

It was evidently observed that the diameter of POF slightly affected the amount of light detected by the LDR. For the same POF volume fraction, fibers of 2 mm diameter yields relatively higher light transmittance than 3 mm fiber diameter. This attribute could be explained as the number of fibers for 2 mm diameter were higher than that of 3 mm fibers, and this affects the brightness region on the surface of translucent concrete and thereby, the amount of light detected. Furthermore, the spacing between the fibers were smaller for 2 mm POF compared to 3 mm POF, and this significantly contributed in amount of light transmitted. Fig. 7 (a) and (b) illustrates the effect of spacing and number of POF on the amount of light transmitted respectively. As it can be seen in Fig. 7 (a), the percentage of light transmitted through translucent concrete decreased when the spacing between POF increased. At 6% POF volume fraction, the spacing for 2 mm fibers is 6.2 mm and a light transmittance of 22.44%, while for 3 mm POF, the spacing is 8.3 mm with a light transmittance of 19.11% (the light transmittance measurement was taken at 100 mm distance of both light source and LDR). The experimental test results obtained in the present study, supports findings by other authors Nikhil et al. [21] and Momin et al. [14]. As illustrated graphically in Fig. 7 (b), the transmittance of light significantly increased as the number of POF increased. Specimens containing 4% of POF volume, 32 and 14 optical fibers were incorporated with 2 mm and 3 mm fiber diameters, and the resulting light transmittance were 18.22% and 15.64% respectively. High number of optical fibers on the surface of concrete increased the interference and superposition of light wave as well as propagation of the transmitted light.



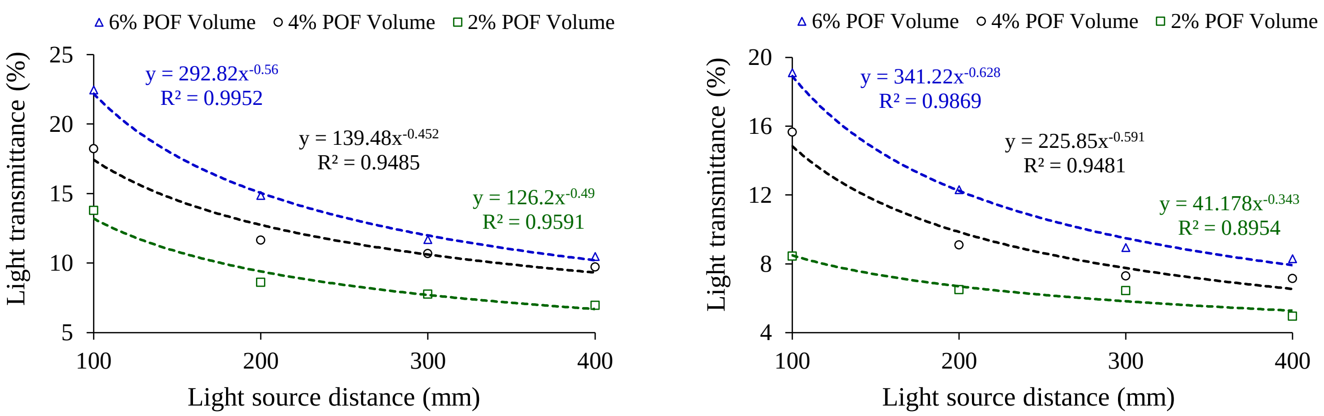
(a) Effect of POF spacing on light transmittance

(b) Effect of number of POF

Figure 7: The effect of POF spacing and number on light transmittance of translucent concrete

Light transmittance analysis at varying distances of light source

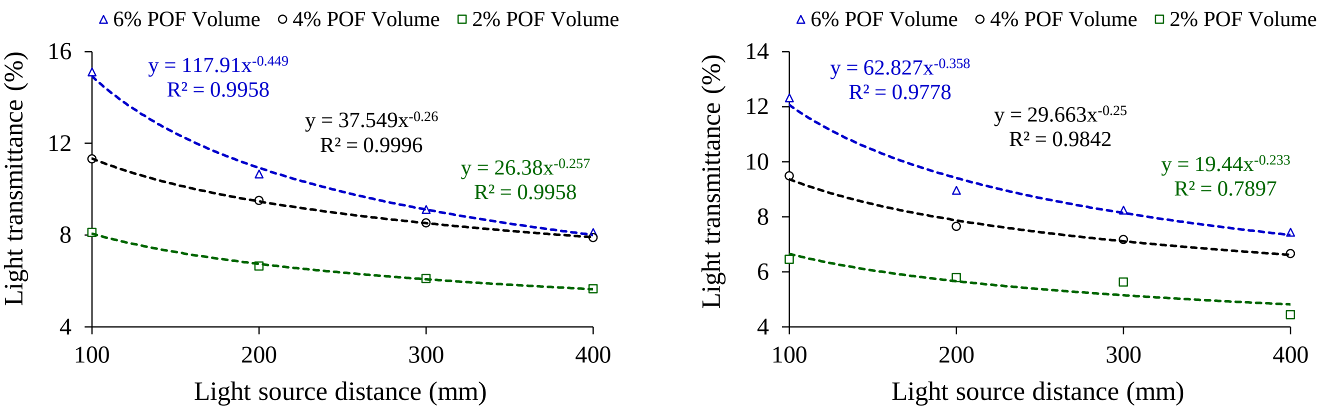
Fig. 8 (a), (b) and Fig. 9 (a), (b) shows the ratio of light transmitted values for specimens situated at 100, 200, 300 and 400 mm distances from the light source during experimentation. Fig. 8 (a) and (b) illustrates the effect of light source distance on the transmittance of light through the prototypes observed at 100 mm of LDR distance. Similarly, Fig. 9 (a) and (b) presents the effect of light source distance when the LDR distance was maintained at 200 mm. It was observed that the transmission of light was significantly decreased with an increasing distance between the translucent concrete specimen and source of light regardless of the volume ratio and diameters of optical fibers. These results concurred with the findings previously reported by Li et al. [13]. The decline rate of light transmittance was the result of gradual decline of the light intensity that approaches the surface of translucent concrete as the distance of light source increased. When the light source distance was increased from 100 mm to 200 mm, the amount of light transmitted decreased significantly, then as the distance increased beyond 200 mm, the decline rate of transmittance decreased gradually. For instance, when the distance from light source to specimen was increased from 100 mm to 200 mm, the rate of light transmittance decreased by 33.84% and 35.62% for specimens containing 6% volume of 2 mm and 3 mm diameters fibers at 100 mm LDR distance respectively. However, when the light source distance increased from 300 mm to 400 mm, the rate of transmittance decreased by 10.35% and 7.33% for fibers diameter of 2 mm and 3 mm respectively. The decline rate of transmittance showed strong correlation in power trendline with respect to the distances of light source.



(a) Ø2 mm POF

(b) Ø3 mm POF

Figure 8: Relationship between light transmittance and light source distance
(At 100 mm LDR distance)



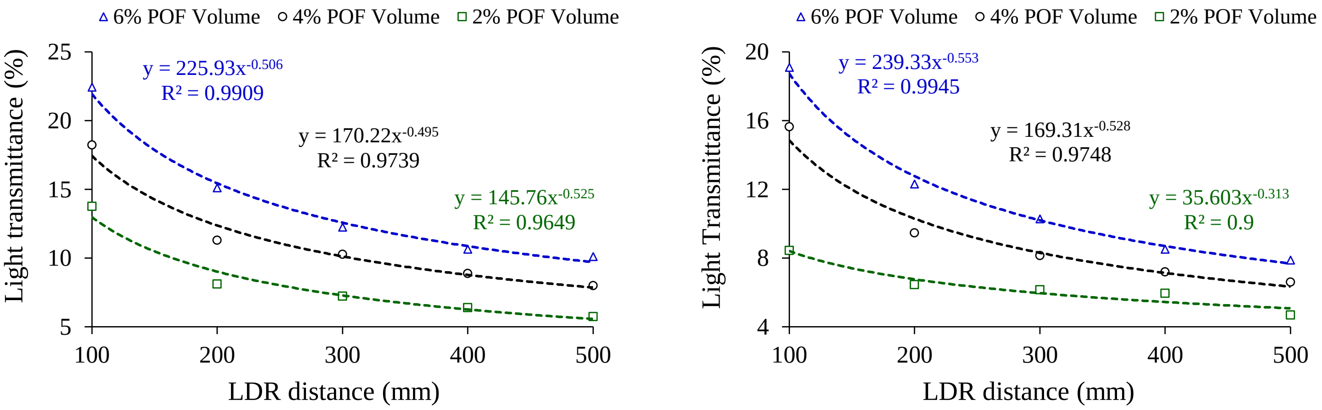
(a) Ø2 mm POF (b) Ø3 mm POF

Figure 9: Relationship between light transmittance and light source distance

(At 200 mm LDR distance)

Light transmittance analysis at varying distances of LDR

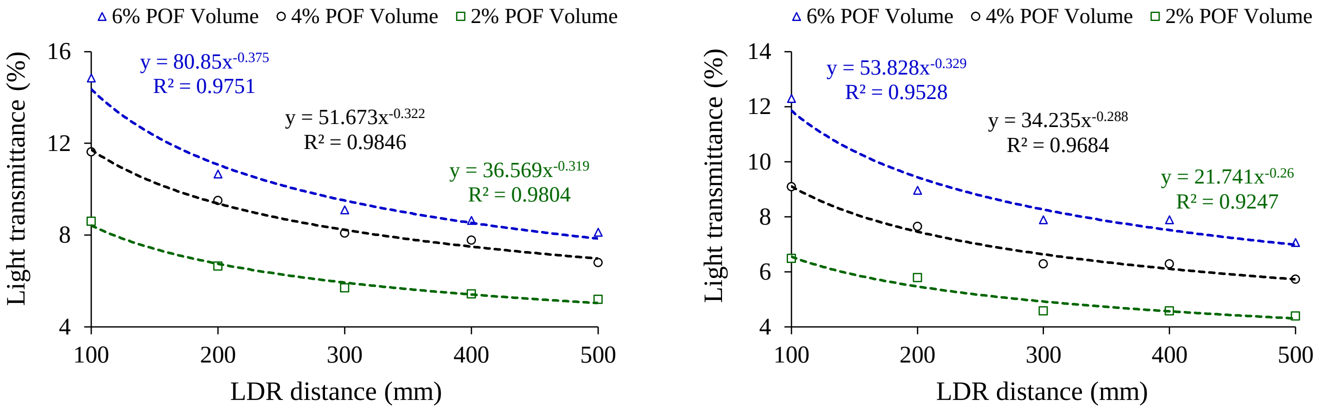
The LDR was measuring the transmitted light through the specimens at 100, 200, 300, 400 and 500 mm distances consecutively. Fig. 9 (a), (b) and Fig. 10 (a), (b) presents the experimental test results of light transmittance at different distances between LDR and specimen. The results appear to show that as the distance between the specimen and LDR increased, the amount of light transmitted decreased remarkably. This can be attributed to the fact that light wave diffracted with distance and consequently decreasing the light intensity and wavelength. The finding on the effect of LDR distance were consistent with the results of study conducted by Li, Li and Guo [15], who reported that optical power decreases with increasing distance between detector and specimen. Variation in relative position of fibers on the surface area of concrete affects the intensity of light received by the LDR. The ratio of light transmittance was decreased significantly when the distance between specimen and LDR ranges 100 – 300 mm. However, when the distance exceeds 300 mm, the rate of transmittance decreased gradually. Generally, the LDR and light source distance showed similar effect on the overall light transmittance of translucent concrete.



(a) Ø2 mm POF (b) Ø3 mm POF

Figure 10: Relationship between light transmittance and LDR distance

(At 100 mm light source distance)



(a) Ø2 mm POF (b) Ø3 mm POF

Figure 11: Relationship between light transmittance and LDR distance

(At 200 mm light source distance)

CONCLUSIONS

According to the experimental results obtained from the research, the following conclusions can be drawn:

- The light transmittance performance of the translucent concrete significantly depends on the percentage volume of optical fibers incorporated.
- The spacing and number of optical fibers considerably affects the overall ratio of light transmitted.
- Light transmittance properties of translucent concrete can be experimentally tested using electrical circuit setup with light dependent resistor (LDR).
- When the distance between the specimen and light source increases, the amount of light transmitted gradually decreases. Furthermore, the intensity of light transmitted through translucent concrete gradually decreases with respect to distance between the LDR and specimen.
- The experimental results evidently show that plastic optical fiber based translucent concrete with 6% optical fibers volume ratio performs up to 22% of light transmittance. Hence, POF of 6% volume ratio is apt for production of pre-cast translucent concrete façades/panels with sufficient light transmittance for different architectural and green buildings application.
- Translucent concrete can be successfully used as energy efficient construction material for sustainable construction and civil infrastructure development.

ACKNOWLEDGEMENTS

This research study was made possible via funding provided by the African Union Commission (AUC) and Japan International Cooperation Agency (JICA) under the Africa-ai-Japan innovation research grant 2017 (JKU/ADM/10B) of the Africa-ai-Japan Project (African Union -*african innovation* - JKUAT and PAUSTI Network Project).

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