

LUMINANCE AND STRENGTH CHARACTERISTICS OF TRANSLUCENT CONCRETE FOR SUSTAINABLE DEVELOPMENT

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Abstract

Natural resource extraction, anomalous climate change, and environmental contamination are the results of population growth and urbanisation. Thus, it is necessary to develop new building practices that will ensure the protection of natural resources while giving top priority to the design of an ecologically friendly and energy-efficient building. This requirement is met by translucent concrete, which allows direct sunlight to penetrate through the material and hence lowers the requirement for artificial energy use. This idea is to use plastic optical fibres mixed with cement mortar to create translucent cubes. The optical properties and strength of transparent concrete are investigated in this study. To make the concrete, three different densities of plastic optical fibres with a 0.75mm diameter are added to a cement mortar. The study's findings demonstrated that when the volume fraction of optical fibre rose, the transparent mortar cube samples' strength characteristics decreased. A specifically designed lightbox and a mobile application with a light lux meter were used to assess the specimens' light transmission capabilities. The results of the testing show that the light intensity increased nonlinearly with the number of optical fibres.

Keywords: Optical Fibre; Strength Characteristics; Sustainable Development; Translucent Concrete

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Introduction

Concrete that transmits light, sometimes referred to as luminous or transparent concrete, is a novel construction material that permits light to flow through its structure (Emanet *et al.*, 2023). A large portion of the world's energy consumption is contributed by the building sector, which comprises approximately 34% of global energy demand (Dhanalakshmi *et al.*, 2023a). Furthermore, lighting accounts for 19% of global electricity use. To reduce light energy consumption and foster sustainable building development, innovative advanced concrete materials, such as light-transmitting concrete (LTC) or translucent concrete, have been developed and introduced to the construction industry (Shenoy *et al.*, 2022a). Traditionally, glass and synthetic composites, including polymers and epoxy resin, are employed to transmit light in structures. The advent of light transmitting concrete (LTC), or transparent concrete, represents a significant advancement in concrete technology, allowing light to permeate the substance and enhance interior illumination within structures (Chiew *et al.*, 2024a). LTC comprises light-transmitting materials, including glass and optical fibre, integrated within the concrete (Luhar *et al.*, 2021). The light transmittance characteristics of LTC facilitate future advancements in architecture and infrastructure with reduced light energy usage (Morris, 2022). Moreover, the advancement of LTC will augment safety and elevate the visual appeal of the structure (Deshmukh *et al.*, 2023). LTC remains very obscure and underutilised in the construction industry compared to other forms of advanced concrete.

This innovative material offers a distinctive and useful answer for architectural design by fusing the strength and structural integrity of conventional concrete with the capacity to transmit light (Ayyanar *et al.*, 2023). The demand for more sustainable and energy-efficient building materials has fuelled the development of light-transmitting concrete (Navabi *et al.*, 2023). To reduce concrete's environmental impact, researchers have concentrated on adding sustainable and renewable materials like agricultural residues as fibre reinforcements (Chiew *et al.*, 2024b). Because light-transmitting concrete uses less energy and produces structures with a less carbon footprint, it has the potential to have a big impact on the construction sector (Li *et al.*, 2021). The importance of building with energy efficiency has grown in the last several years (Kantatham *et al.*, 2024). Approximately thirty percent of India's total energy usage occurs in residential and commercial structures, despite the

country's dense population. (Krishna, 2023). As India becomes more urbanised, there will undoubtedly be a greater demand for energy usage. Growing energy demand will result in increased power production, which will have an impact on the nation's natural resources and capital (Loganayagan, 2022).

At the moment, fossil fuels account for 80% of India's electrical production (Antony Samy *et al.*, 2023). The burning of coal releases CO₂ which is one of the reasons to produce greenhouse gases (Amit *et al.*, 2024). As a result, this directly affects our environment, health, and climate (Dhanalakshmi and Shahul Hameed, 2024). Therefore, creating a strategy to reduce building energy usage and cut down the greenhouse gases in the atmosphere is the ultimate aim (Dhanalakshmi *et al.*, 2023b). The development of light-transmitting concrete is a noteworthy development in the building industry (Nam *et al.*, 2023).

Low-rise structures are supplanted by high-rise structures and skyscrapers (Radha *et al.*, 2024). This is a challenge in obtaining natural light in buildings due to the barrier caused by adjacent constructions (Chiew *et al.*, 2021). The issue has significantly increased the reliance on artificial lighting sources for buildings (Rajendra Prasath *et al.*, 2023). It is imperative to minimise artificial light usage in structures (Mohan kumar *et al.*, 2020). This study presents an overview of the evolution of light-transmitting concrete. Transparency in concrete is enhanced by the incorporation of optical fibres (Shenoy *et al.*, 2022b). The implementation of LTC in construction facilitates light transmission, hence decreasing energy consumption and carbon emissions, resulting in a more sustainable living environment (Vychytil and Hájek., 2023). This research examines the contemporary advancements and use of LTC. There remains a deficiency in the examination of the physical and mechanical properties of LTC, particularly concerning its applications in structural performance. Additional research is necessary to examine the fibre-matrix interfacial bond strength of LTC, and actions should be implemented to enhance the mechanical strength of LTC.

The main aim of this project is to use renewable energy sources inside of buildings. By allowing natural daylight, it has the ability to dramatically lower building energy use, improving sustainability and lowering energy expenses in the building (Hoy *et al.*, 2020).

In this investigation, a cube of cement mortar was filled with 0.75 mm diameter plastic optical fibres of three different densities in an attempt to

find out the strength properties of translucent concrete. Another goal was to investigate how much energy can be saved for illumination by using transparent building panels. Thirty percent of the electricity used in homes is used just for lights (Samingthong *et al.*, 2023). As a result, it is essential to utilise natural light to brighten interior spaces in structures. Even during the day, rooms in highly populated urban regions with closely spaced tall buildings frequently lack natural light, leaving them dark (Sharifi *et al.*, 2023). These kinds of difficulties will be solved with the help of translucent concrete, which allows light to pass through because it contains either glass or plastic optical fibres (Shahmir and Bhat, 2020). Luminous concrete is a good option for achieving the desired balance of strength and beauty and effectively utilising natural light (Hoy *et al.*, 2024).

Materials and Methods

The materials needed for this experimental study included standard Portland cement (grade 53), M-sand (fine aggregate), water, and 0.75 mm plastic optical fibre. The different used sections were listed in Table 1.

Table 1. POF with density variations

S.No	Size of the section	No. of Needles (fibers in surface area of 70.06mm × 0.06mm)
1	5×5	25
2	6×6	36
3	7×7	49

It was crucial to adhere to the experimental procedure before evaluating the samples; this included setting up the mould, mixing the mortar, pouring the material, letting it cure, and then getting the specimens ready for testing. Making a mould is the first step in the process of making light-transmitting concrete. Plywood and cast iron are just two of the materials that can be used to build the mould prototype. The vertically drilled holes on the mould's two opposing sides were threaded with optical fibre. The light transmission component used in this experiment is a 0.75mm dia. plastic optical fibre that comes in three different densities, such as 5×5, 6×6, and 7×7 as shown in Figure 1. There are 25 holes in total on a single (5×5) density mould. After being placed into the holes, two POF numbers are activated. As shown in Figure 1, the density mould (6×6) has a total of 36 holes, while the density mould (7×7) has a total of 49 holes.

Fabrication of moulds began with plywood pieces whose holes accurately received optical

fibres before mould release. Weaving of optical fibres are shown in Figure 2. Oil applied to interior surfaces permitted easy removal of the mould. A combination mixture of standard Portland cement and M-sand was placed into moulding structures with equal distribution of fibres through vibration until voids disappeared. Following 24 hours of initial setting time, the samples went through submersion in water according to IS requirements for 28 days before moving to air drying followed by mechanical testing. The size of the specimen is 70.6×70.6×70.6 mm. Next, the optical fibres were polished to enhance their light transmission capabilities for evaluation.



Figure 1. Arrangement of plastic fibre optic cable for (5×5), (6×6), (7×7) densities



Figure 2. Weaving of optical fibres

The vertically drilled holes on the mould's two opposing sides were threaded with the optical fibre. Examples of light-transmitting mortar cubes were made by carefully pouring M-sand mortar into the cement and coating the internal surface of the mould with mould oil. There were three cubes produced for every fibre density. Every layer is condensed using the vibrator machine. It's crucial to make sure the top surface is level once the mortar has been placed. Twenty-four hours after the casting was finished, the mould was taken out. The purpose of the strength test was to determine how the compressive strength of the light-transmitting mortar cubes was affected by the various densities of optical fibres. In compliance with IS guidelines, concrete cubes with a size of 70.6×70.6×70.6mm, mortar cylinders with dimensions of 100×200 mm, and prisms with dimensions of 500×100×100mm were constructed to evaluate the properties of the concrete. Three different densities of plastic optical fibres were used to create a total of eighteen cubes, and their compressive strength was measured at seven and

twenty-eight days. The liquid must be allowed to dry in the air for a full day after being poured into the mould. The specimen can then be taken out of the mould at this point. Following its extraction from the mould, the specimen is submerged in water for a 7-28 day curing period. Following a 28-day curing period, the specimen is taken out and allowed to air dry entirely. To improve light transmission via the optical fibres, the protruding sections of the fibres from the cubes and cylinders were polished and trimmed with a knife or blades before testing.



Figure 3. Measurement of Lux Angles



Figure 4. Light transmittance and measurement of lux values

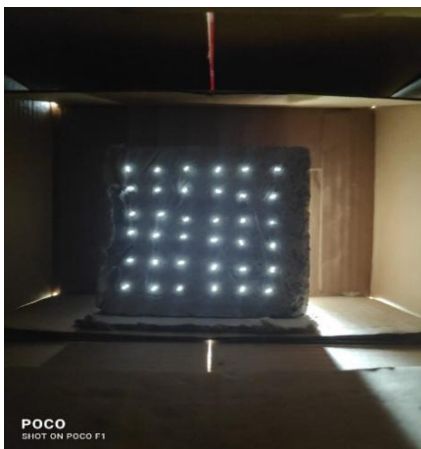


Figure 5. Sunlight passing through the mortar cubes during daytime

Test Method for Light Transmitting Properties

Lux meters, spectrometers, and light-dependent resistors (LDRs) are a few tools for measuring light (Wang and Chi, 2023). Nonetheless, a new and straightforward solution has surfaced with the usage of an Android mobile application that has a light-lux meter built in. The measurement of lux angles are shown in Figure 3. This program measures the quantity of light in lux levels using an integrated sensor and shows the results on a graph. A technique was used to investigate the concrete's ability to transmit light. To do this, a lightbox had to be made, and a 35-watt incandescent lamp with a tungsten wire filament had to be placed on one side of the lightbox. Inside a sample window, the specimen was placed in the centre. An Android smartphone with a light lux meter app installed was positioned on the other side. A hollow enclosure was used to stop unnecessary light from entering the space. One side included an optical fibre-equipped mortar cube, and the other side featured an Android smartphone fitted with a light lux meter software as shown in Figure 4. One tool for measuring light intensity is a lux meter. A photocell sensor is used in this application to measure and record light intensity. To measure the brightness that passes through the specimen window with and without the LTC sample, a stationary lux meter was placed within the lightbox. Through this method we can find out how much light had entered the concrete. Sunlight passing through the mortar cubes during daytime and Light transmittance of translucent prism are shown in Figure 5 and Figure 6.

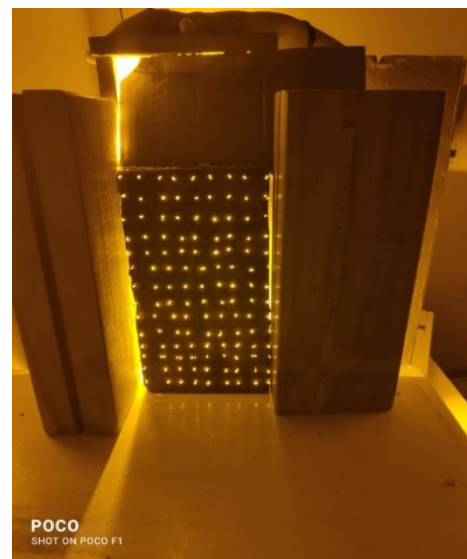


Figure 6. Light transmittance of translucent prism (500mm×100mm×100mm)

Results and Discussion

Compressive strength:

Figure 7 illustrates the test results of the compressive strength of concrete with the addition of optical fibre at the ages of 7 days and 28 days, correspondingly.

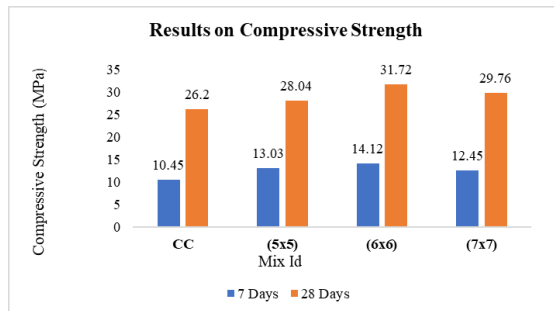


Figure 7. Test results on Compressive strength of concrete

The cracks propagate vertically along the height of the specimen, suggesting brittle failure. This occurs due to the inability of the concrete matrix to resist tensile stresses induced by compression. Incorporating polymer-based additives or hybrid fibre reinforcement to delay crack propagation, as shown in Figure 8.

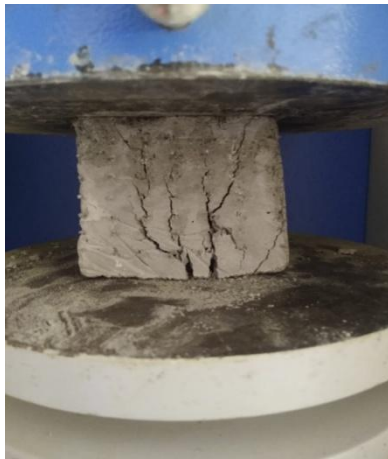


Figure 8. Failure Pattern of LTC

Figure 9 depicts the relationship between various concrete mixes and their respective compressive strengths after 7 and 28 days of curing. The graph offers a preliminary overview of the compressive strength behaviour of different concrete mixes with linear expression and R^2 values, respectively. Plotting the findings of 28 days strength revealed that the 6x6 density specimen had a maximum strength of 31.72 N/mm², which was approximately 13.12% greater than the 5x5 density

and 21.06% greater than the normal concrete. Based on the aforementioned findings, it appears that compressive strength rises in tandem with fibre density. The 7x7 density specimen shows decremental values of compressive strength of 29.76 N/mm². In actuality, the compressive strength of the 7x7 fibre density specimen was 6.5% lower than that of the standard specimen. The higher-level optical fibres that were introduced, which seldom made contact with the cement mixture, are the cause of this outcome.

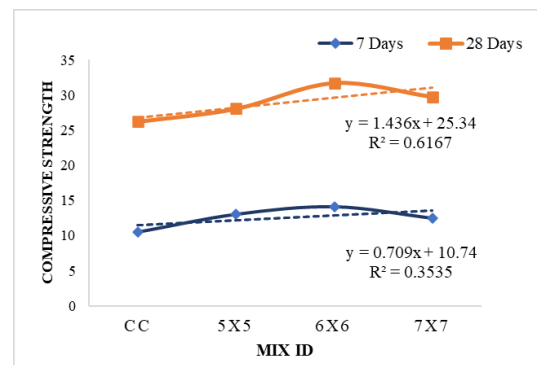


Figure 9. Visualising trends and correlations of compressive strength

The strength development of the cement matrix strongly depends on the contact region between plastic optical fibres (POFs) and the cement matrix. The stress distribution pattern of the composite changes because POF inclusion affects matrix continuity. Standard concrete strength measurements increased by 21.06% when the experimental specimen used six times six fibres, reaching 31.72 N/mm² maximum compressive strength. The embedded fibres enhance the load transfer mechanism because they operate as micro-reinforcements to create this increase in strength.

A reduction in strength following an addition of fibre content with a certain percentage increase may be caused by the introduction of an increasing number of voids, which breaks the matrix's continuity and reduces the density of the concrete. The incorporation of plastic optical fibre into concrete materials can significantly enhance their compressive strength, provided that the percentage of fibre does not surpass optimal limits.

Split tensile strength:

Figure 10 shows the test results of split tensile strength for the ages of 7 days and 28 days and tabulated.

The researchers obtained a maximum tensile strength of 3.88 MPa by comparing translucent concrete specimens with regular concrete using

optical fibres of varying density. Conversely, normal concrete has a maximum strain of 3.17 MPa and sudden material breakdown. Generally speaking, increased fibre content makes materials tougher and more resistant to cracking, but if the fibres are not distributed properly, it can also cause the initial tensile strength to fall. The development of voids as the fibre content increases can be the reason for the strength loss that is noticed at a particular point in the fibre content of (6×6). As a result, the concrete becomes less dense, and the matrix's continuity is broken.

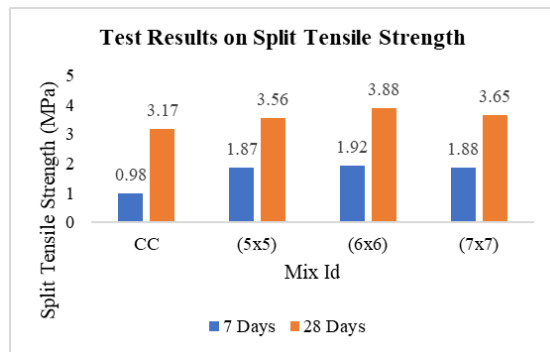


Figure 10. Test results on split tensile strength

Flexural strength:

Flexural strength testing is done on a conventional 500×100×100 mm prism, and the test results can be compared to those of a nominal prism for 7 and 28-day durations. The test on the prism using two-point loading yields the concrete's flexural strength, as shown in Figure 11.

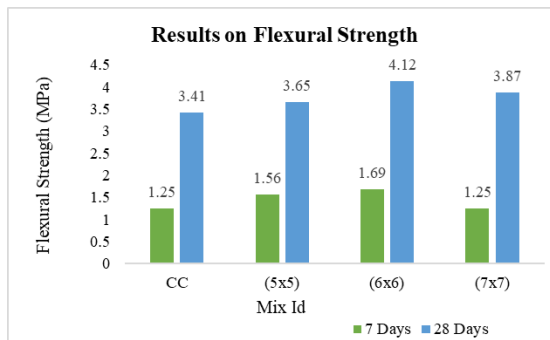


Figure 11. Effect of plastic optical fibre on flexural strength

The flexural strength of translucent concrete changed according to the number of plastic optical fibres (POFs) present in the mix. When looking at flexural strength at 28 days, it is found as 4.12 MPa for 6×6 fibre density, while conventional concrete measured 3.41 MPa. This value indicates a 20.8% increase in strength. A higher number of plastic

optical fibres in the 7×7 fibre density group decreased flexural strength to 3.87 MPa because the material lacked uniformity due to additional void formation. The 6×6 fibre density group achieved a maximum flexural strength value of 4.12 MPa. The experimental results demonstrate that POF incorporation improves flexural strength, but excessive fibre amounts reduce it through broken connections within the cementitious material.

Light Transmission Test

Figure 12 shows the results of the lux values of the test specimen. The cube with a 7×7 density of optical fibre was found to have the highest level of brightness, with a face illumination intensity of 22 lux. The cube exhibiting a 6×6 optical fibre density was found to have the most illumination, yielding a brightness of 20 lux. Lastly, a cube with a 5×5 optical fibre density showed 17 lux of illumination. When comparing the 5×5 fibre density concrete cube to the 7×7 fibre density concrete cube, there was a 22.7% increase in light transmission intensity.

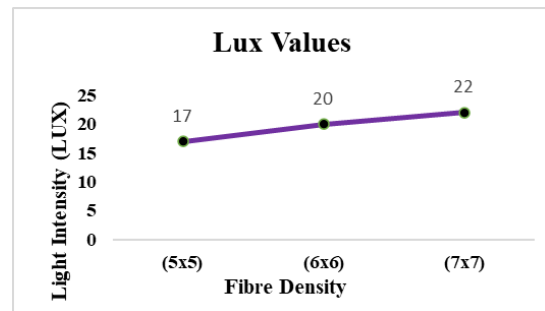


Figure 12. Lux values for mortar cubes for three different fiber densities

A mobile application-based lux meter offers a new method to measure light intensity in translucent concrete specimens with benefits of accessibility and innovation compared to standard lux meters. The results show that the amount of optical fibre included in a concrete cube strongly correlates with the amount of light that can travel through the material. As a result, when optical fibre density rises, so does light transmission intensity. Because light penetrates more easily through light-transmitting concrete, it has been observed that room brightness can improve by as much as 30%. The lux value without LTC is 15.4 lux, and with LTC, the (7×7) fibre density shows the lux value of 22.

For validation, measurement of light transmission intensity through the concrete cube, the apparatus known as a lux meter was used as shown in Figure 13. The accuracy of standard lux

meters reaches ± 1 -5% approximately because they contain calibrated photodiodes with a precise spectral response, but mobile sensors fall short at ± 10 -30%. Additional advancement in smartphone sensor calibration systems will increase their value for scientific research applications.



Figure 13. Setup for measuring lux values

Conclusion

The following findings are made in light of translucent concrete's production, compressive strength, and light transmission capabilities:

- **Evaluation of Strength:** The result of fibre density analysis shows that the 6×6 fibre density had achieved the highest compressive strength, which is 31.72 N/mm², which was 13.12% higher than 5×5 and 21.06% higher than standard concrete. However, 7×7 density had a lower value as a result of fibre congestion and voids that were present in the same.
- **Light Transmission:** It was also seen that the specimen with a 7×7 fibre arrangement had the maximum value of light intensity of 22 lux.
- **From the mechanical perspective,** although 5×5 had lesser reinforcement, still 6×6 shows a perfect balance to extend the mechanical properties without making them rigid and heavy. It is found that among the fibre parameters, fibre density, diameter, and spacing influence the level of translucency.
- **Optimisation of Daylighting & Energy Saving Possibilities:** By using translucent concrete, energy efficiency is a factor as well. It has potential for the development of green structures, especially in areas of congestion such as India.

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