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THERMAL AND DAYLIGHTING PERFORMANCE OF TRANSPARENT CONCRETE IN PENANG, MALAYSIA

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ABSTRACT

Modern technology studies and research developments have enhanced the quality and innovation of concrete. Transparent concrete is concrete that has light-transmitting properties which transmit light through the optical fibre. Optical fibres are reinforced in the conventional concrete mixture from one face to another face, which allows direct light to transmit through it. Daylighting factor is one of the fundamental qualities of the energy efficiency of a building. The thermal performance is also crucial to providing comfort to the building occupants. The literature studies cover the light transmittance and thermal performance of transparent concrete. Selected literature studies are reviewed based on the related topic, Asian countries, and countries with a similar climate to Malaysia. This research applies quantitative method where it was focus on experimental study to transparent concrete. The overall result indicates improvement on light transmission and thermal performance as the plastic optical fibre increased compared to conventional concrete. The total average outdoor surface temperature of transparent concrete shows a difference of 0.989°C lower than conventional concrete. The total average temperature different between

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conventional concrete and transparent concrete (560 optical fibre) are 0.9°C. This experiment's significant contribution is that using more plastic fibre optic reduces thermal conductivity and heat gain while allowing for greater daylighting. Finally, transparent concrete shows effectiveness on light transmission and thermal resistance where it can contribute to building industry on green building and sustainable design. However, the further studies on thermal performance with longer duration is required to analyses the thermal heat loss.

Keywords: *Concrete, Daylighting, Optical Fibre, Thermal Performance, Translucent Concrete.*

INTRODUCTION

Concrete has been utilised since the Roman era although its essential components have not changed. Common concrete is made of cement, sand, aggregates, and water. Engineers have developed many types of concrete by using new technology (Shetty et al., 2019). Transparent concrete, also known as light transmission concrete or translucent concrete, is a new technology form of concrete that transmits light through it using optical fibre. The novel material is also considered as green building material. The transparent concrete is made of cement, very fine sand, and thousands of optical fibres reinforced in concrete from one face to another face that allows directly the light to go through it. (Zhang et al., 2020).

The concept of integrating natural illumination into the architectural design is known as daylighting. Daylighting may have a significant impact on building energy efficiency if effectively designed and constructed (Ahmad & Reffat, 2018). Transparent concrete (Figure 1) is a type of concrete that helps to maximise daylighting. A well-designed daylighting system may reduce lighting energy use while also increasing visual comfort, health, and amenity for inhabitants (Wong, 2017). The daylight factor is a particularly significant consideration in evaluating energy consumption due to artificial lighting application. However, many nations worldwide also employ DST (daylight saving time) as an energy conservation measure (Baloch et al., 2018).

Thermal insulation is a fundamental factor that helps to achieve thermal comfort for building occupants. The major heat transmission mechanisms-conduction, radiation, and convection-can be reduced by implementing appropriate building techniques and material selection. (Asadi et al., 2018). According to Abdullah et al. (2016), discomfort issues have been attributed to the effect of solar radiation and climate in tropical countries like Malaysia. Furthermore, many commercial buildings feature glass curtain walls as building façades which causes thermal discomfort for the inhabitants (La Ferla, 2020). Glazed façade is identified as weakest area as it allows heat gain from direct sunlight. The studies shows that highly glazed buildings have substantially higher solar gains than conventional buildings. Transparent concrete is a new technology material where not many countries manufacture the material including Malaysia. In addition, the study of transparent concrete especially on thermal performance and suitability as building material in tropical climate countries are limited (Hwang & Chen, 2022). The focus of this research is to study and observes the effectiveness of transparent concrete toward improving the daylighting and thermal performance in a building. This study also investigates the result of transparent concrete on accumulating daylighting in a building and optimize the transparent concrete on thermal performance in indoor space of a building by applying transparent concrete.

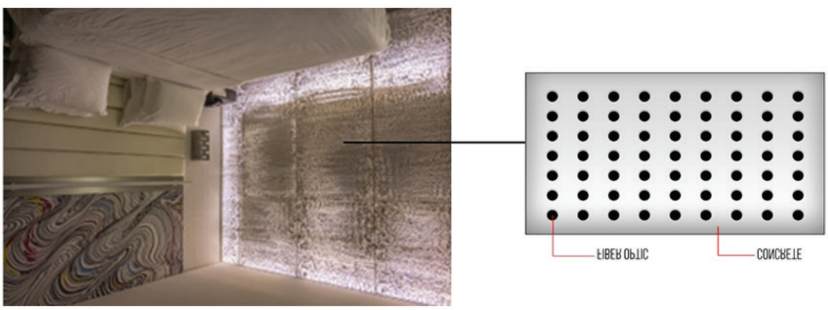

Figure 1. Example of Transparent Concrete Wall Applied in Bedroom
Note. (Adapted from Transparent Concrete | Materials, Use, Advantages & Disadvantages of Transparent Concrete. Dream Civil, 2022, Dream civil. (https://dreamcivil.com/transparent-concrete)

LITERATURE REVIEW

According to Chiew et al., (2018), the major purpose of transparent concrete is to maximise daylight while reducing electric power use and using optical fibre to detect structural stress. Transparent concrete allows light to penetrate through it, enabling visibility and minimising the amount of light energy required by the structure. Furthermore, it transmitted more light than conventional concrete.

Based on Pilipenko et al., (2018), transparent concrete is aesthetic and architectural purposes such as building envelope and exterior decorative material. The novel material also can be applied on walls, partitions, and ceilings instead of windows and conventional materials. It can be also used in dark spaces or area such as subway stations and tunnels where the light from ground level or exterior transmits into the area. The studies shows that transparent concrete provides 22% light transmittance which is sufficient illumination for residential and commercial buildings (Shitote et al., 2018). Table 1 indicates the recommended illuminance for residential and non-residential space by Malaysian Standard MS 1525 and MS 2680 (Awang et al.,2020).

The inclusion of optical fibres in conventional concrete improved the thermal resistance and mechanical properties. Thus, the number or ratio of optical fibres in the concrete mixture also determines the compressive strength even though the transparent concrete is lighter weight compared to conventional concrete (Momin et al., 2014). The studies also show that chopped glass fibre added to a concrete mixture reduced thermal conductivity under high temperatures (Wang et al., 2020). In addition, the use of the material has decreased the thermal conductivity and improved the total thermal resistance (Ahuja & Mosalam, 2017).

Conventional concrete display as raw texture in contrast to transparent concrete, which delivers a unique look and increases aesthetic values in daytime and lantern during the night (Dhanke et al., 2020). During the night, the artificial light in the space or area transmits light towards the exterior wall and enhances the overall aesthetic value of the building. The design and texture of the transparent concrete can be varies depending on the arrangements of the optical fibre during casting the block or panel (Sahithi & Mouunica, 2019).

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Table 1. Recommended Illuminance for Spaces

Area	Recommended Illuminance (Lux)
Residential	
Dining Room	250
Kitchen	250
Non- Residential	
Infrequently used area (example: interior walkway, stores, corridor, gate house, lobbies, waiting room)	100-300
Infrequent reading and writing, restaurant	200
General office, shops, drawing office	300-400
Classroom, Library	300-500
Museum and gallery	300

(Adapted from Malaysian Standard MS 1525 and MS 2680)

RESEARCH METHODOLOGY

This research employs quantitative methods by experimental study of physical models for numerical results on daylighting and thermal performance. The experiment was done at Penang, Malaysia. For this experiment, the Sika Grout -215 was used. The ingredient of the material is included with cement, sand, and maximum grain size of 1.2mm. Coarse aggregates were not used in the experiment due to construction issues. However, 6mm fibreglass chopped strands (Figure 2a) were applied to replace coarse aggregates. 1mm poly methyl methacrylate (PMMA) fibre optic cables (Figure 2b) were used in this experiment to ensure transparency for the cement concrete block matrix. The parameters applied for this experiment as shown below:

-Fixed variables: Ratio of concrete mixture, size, and thickness of concrete block

-Manipulated variables: Ratio of poly methyl methacrylate (PMMA) fibre optic

-Responding variables: Temperature, light intensity

Figure 2: a) 6mm Fibreglass Chopped Strands, b) 1mm Poly methyl Methacrylate (PMMA) Fibre Optic Cables

(Source: Author)

Phase 1: Mould Production Process

The production process of mould for the transparent concrete used 3mm acrylic sheet and high duty tape. Initially, the design and dimension of 9cm(L) x 4cm(W) x 9cm(H) were prepared using AutoCAD software to ensure the moulds are accurate in sizes. The number and distance between holes are varied (5mm and 2.5mm) which determines the degree of light transmission and thermal resistance. Then, the prepared mould design was carefully cut using laser cutter machine and poly methyl methacrylate (PMMA) fibre optic were arranged according to the holes in the mould as shown in Figure 3.

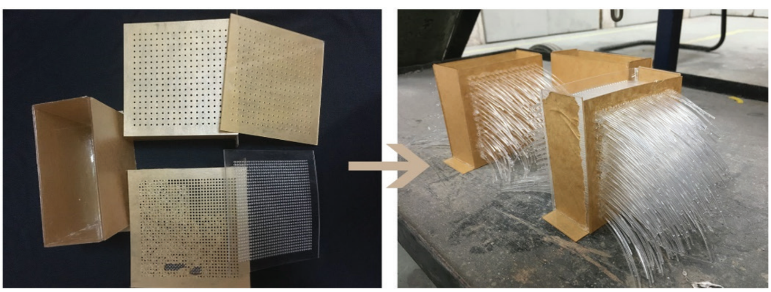

Figure 3. Arrangement of Plastic Fibre Optic in Mould

(Source: Author)

Phase 2: Mixture and Transparent Concrete Production Process

In the experiment, the coarse aggregates were excluded from the concrete mixture and Sika Grout- 215 were applied to avoid fibre balling issues caused by narrow gap between transparent materials during pouring of high-fluidity concrete in the block. The concrete mix design is summarised in the Table 2 below. The Sika Grout-215 gradually added into a clean container while continuously mixing with water and fiberglass chopped strands until the consistency is obtained. The mixture was mixed for 3 minutes with slow speed drill and the final concrete produced and poured into prepared mould with arranged poly methyl methacrylate (PMMA) fibre optic. After room curing for at least 48 hours in the mixing process, the samples (Figure 4) were proceeded to 28 days of curing in water and perform with grinding to remove mould.

Table 2. Mix Proportion

Sample Number	Sika Grout-215 (kg)	Water (litre)	Fibreglass Chopped Strands (kg)	Poly Methyl Methacrylate (PMMA) Fiber Optic (Number)
A	1.84	0.31	0.368	-
B	1.84	0.31	0.368	290
C	1.84	0.31	0.368	560

(Source: Author)

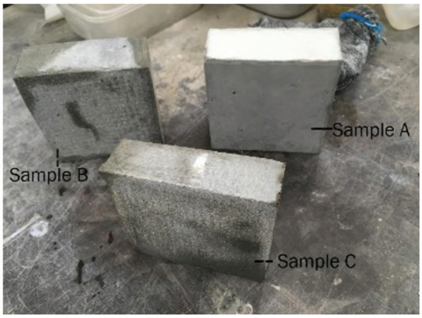

Figure 4. Samples of Concrete

(Source: Author)

Phase 3: Light Transmittance Test

The light transmittance of the concrete samples measured by the amount of light passing through the transparent concrete. HANNA HI 97500 portable lux meter shown in Figure 5a was used to measure illuminance of the transparent concrete. It can be measured in range of 0.001 to 199.9 Klux. The light source input was from natural sunlight during sunny days. According to Dobrijevic, (2022) the month of June was selected because the sun reaches its highest and northernmost points in the sky during June solstice. It also delivers the maximum daylight hours of the year 2022. The test was measured by using lux meter (Klux) as shown in Figure 5b and the result converted into lux (lx). A box was made up using mounting board to prevent light escape while carrying out the test.

Figure 5: a) HANNA HI 97500 portable lux meter, b) Light intensity test

(Source: Author)

Phase 4: Thermal Test

The thermal test of concrete samples measured by the amount of heat transferred to the transparent concrete. Flir i7 infrared thermal imaging camera (Figure 6a & Figure 6b) was used to measure the outdoor surface temperature (Celsius). The temperature range of this equipment are -20°C to 250°C. IR400 EXTECH infrared thermometer was used to measure indoor surface temperature (Celsius). The temperature range of this equipment are -20°C to 332°C. Based on (Awang, 2021), the study shows the hottest hour of the day occurs between 3pm to 5pm which are 3 to 5 hours after noon. It is because of the Earth's surface receives and absorbs heat at a faster rate than it can radiate until mid- to late afternoon, when the process reverses. However, the local weather shows 12pm to 2pm has the highest outdoor temperature on 3 days of experiment. Both test result was recorded

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at range from 12.40pm to 2pm which has interval of 15 minutes with total of 30 minutes by placing the transparent concrete under the sun as shown in Figure 7a and Figure 7b. The total duration of this test took 10 days, but the actual result was recorded for 3 days due local weather conditions. It is because the thermal test was decided to be done during clear sky which helps on precision of the result.

Figure 6: a) Flir i7 Infrared Thermal Imaging Camera, b) Outdoor Surface Temperature Test

(Source: Author)

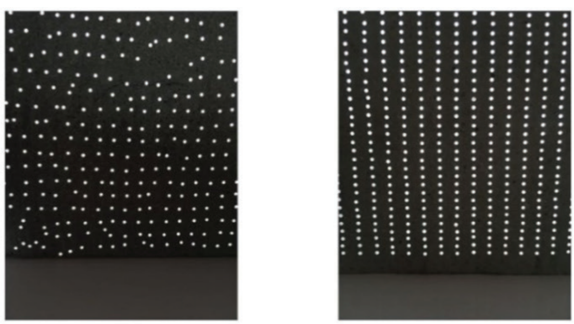
Figure 7. a) IR400 EXTECH Infrared Thermometer, b) Indoor Surface Temperature Test

RESULT AND DISCUSSION

Effect of Daylighting on transparent concrete

The daylighting performance result of three concrete samples were recorded under the same circumstance. In addition, the result of day 1 (Table 3) shows that the light illuminance of transparent concrete (560 optical fibre) is higher than the transparent concrete (290 optical fibre). The result of this experiment varies with different duration due to variable in light intensity from sunlight.

However, the result for day 2 (Table 4) and day 3 (Table 5) shows that the transparent concrete with higher number of fibre optic deliver higher light intensity even the local weather (°C) differs on 3 days. Figure 8 shows the image of transparent concrete placed in the mounting board during daylighting test. Experimental result of average light illuminance is shown in the Figure 9 and several observations can be made. The comparison of overall average result shows the constant result on both transparent concrete samples for 3 days. The result in Figure 9 indicates the fibre optic able to transmit lights from one face to another face. It also shows that using more fibre optics in the concrete to allow more daylighting. The result also shows the total average light illuminance is sufficient for spaces as shown in Table 1.



Transparent Concrete (290 Optical Fiber)   Transparent Concrete (560 Optical Fiber)

Figure 8. Interior Image of Transparent Concrete

(Source: Author)

Table 3. Daylighting test result (Day 1), 7/6/ 2022 (Outdoor Temperature: 31 °C)

Duration	Light Illuminance / lux (Daylight)		
	Conventional Concrete	Transparent Concrete (290 optical Fiber)	Transparent Concrete (560 optical Fiber)
0 minute	-	245	330
15 Minutes	-	282	325
30 Minutes	-	278	318
Average Light Illuminance	0	268	324

(Source: Author)

Table 4. Daylighting test result (Day 2), 8/6/ 2022 (Outdoor Temperature: 30°C)

Duration	Light Illuminance/ lux (Daylight)		
	Conventional Concrete	Transparent Concrete (290 optical Fiber)	Transparent Concrete (560 optical Fiber)
0 minute	-	237	340
15 Minutes	-	273	312
30 Minutes	-	257	298
Average Light Illuminance	0	256	317

(Source: Author)

Table 5. Daylighting test result (Day 3), 9/6/ 2022 (Outdoor Temperature: 32°C)

Duration	Light Illuminance / lux (Daylight)		
	Conventional Concrete	Transparent Concrete (290 optical Fiber)	Transparent Concrete (560 optical Fiber)
0 minute	-	290	325
15 Minutes	-	297	316
30 Minutes	-	210	308
Average Light Illuminance	0	266	316
Total Average Light Illuminance		263	319

(Source: Author)

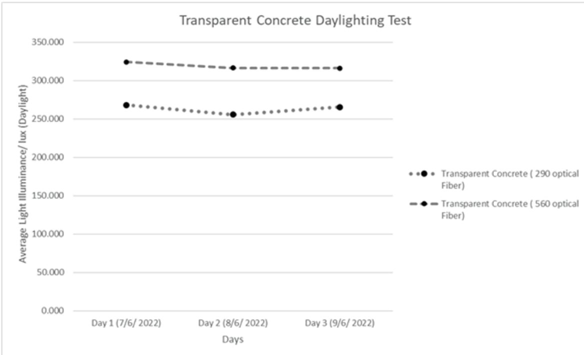


Figure 9. Interior Image of Transparent Concrete

(Source: Author)

Effect of Solar Radiation on the External Surface of Transparent Concrete

The results are shown in Table 6, Table 7, Table 8, and Figure 10. The conventional concrete shows the highest average temperature at 0 minute, 15 minutes and 30 minutes compared to transparent concrete (290 optical fibre) and transparent concrete (560 optical fibre). The thermal image displays the level of heat transferred to the concrete samples. The blue colour indicates the coolest area and gradually increase to green, yellow, and red indicates the highest temperature at the concrete. The thermal image shows the colour gradually turn from blue to green at small area at below all 3 concrete samples after 15 minutes. At 30 minutes, the thermal image shows green and yellow gradually develop in bigger area of the concrete samples. The conventional concrete indicates larger area with green and yellow colour compared to transparent concrete (290 optical fibre) and transparent concrete (560 optical fibre). Instead, the transparent concrete (560 optical fibre) results the smallest area of green and yellow colour based on the thermal image at 30 minutes.

The maximum temperature drops on day 1 between conventional concrete and transparent concrete (560 optical fibre) are 1.44 °C. The maximum temperature drops on day 2 between conventional concrete and transparent concrete (560 optical fibre) are 0.67 °C. The maximum

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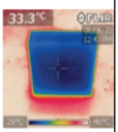
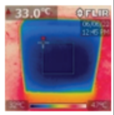
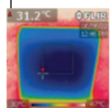
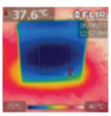
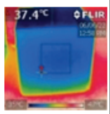
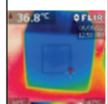
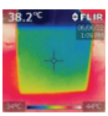
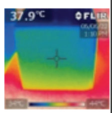
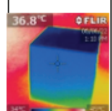
temperature drops on day 3 are 0.87 °C. The total average temperature different between conventional concrete and transparent concrete (290 optical fibre) are 0.433°C. The total average temperature different between conventional concrete and transparent concrete (560 optical fibre) are 0.989°C. The total average temperature different between transparent concrete (290 optical fibre) and transparent concrete (560 optical fibre) are 0.556°C.

Based on Figure 10, the overall result shows the thermal conductivity of the concrete with poly methyl methacrylate optical fibre is lower than conventional concrete. It also shows the higher usage of fibre optic has result less thermal conductivity. The highest temperature drops on day 1 with high surface temperature indicates more effectiveness of fibre optic. Therefore, the plastic fibre optic shows greatest effect on thermal resistance compared to conventional concrete.

Effect of Solar Radiation on the Internal Surface of Transparent Concrete

The results are shown in Table 6, Table 7, Table 8, and Figure 11. The transparent concrete (290 optical fibre) and transparent concrete (560 optical fibre) shows the lowest average indoor surface temperature at 0 minute, 15 minutes and 30 minutes compared to the conventional concrete. The total average temperature different between conventional concrete and transparent concrete (290 optical fibre) are 0.27°C. The total average temperature different between conventional concrete and transparent concrete (560 optical fibre) are 0.99°C. The total average temperature different between transparent concrete (290 optical fibre) and transparent concrete (560 optical fibre) are 0.56°C. The overall result shows the thermal resistance of the transparent concrete with poly methyl methacrylate optical fibre is higher compared to conventional concrete as shown in Figure 11. Based on Figure 12, transparent concrete (560 optical fibre) has the highest temperature different compared to transparent concrete (290 optical fibre) and conventional concrete. It indicates the usage of optical fibre improve the effectiveness on thermal performance.

Table 6. Thermal Test Result (Day 1), 7/6/ 2022
(Outdoor Temperature: 31 °C, 12.40pm)

Time	Conventional Concrete			Transparent Concrete (290 optical Fiber)			Transparent Concrete (560 optical Fiber)		
	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)
0 minutes	 33.3	31.8	1.5	 33.0	31.4	1.4	 31.2	30.2	1.0
15 minutes	 37.6	36.9	0.7	 37.4	36.5	0.9	 36.8	35.7	1.1
30 minutes	 38.2	37.6	0.6	 37.9	37.1	0.8	 36.8	35.9	0.9
Average Temperature	36.37	35.4	0.93	36.10	35.0	1.03	34.93	34.3	1.00

(Source: Author)

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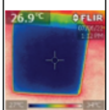
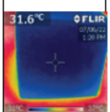
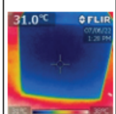
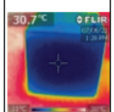
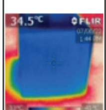
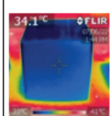
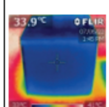
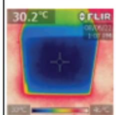
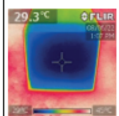
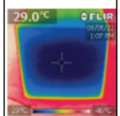
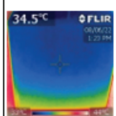
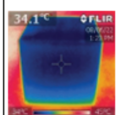
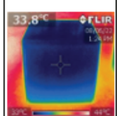
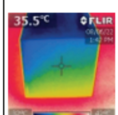
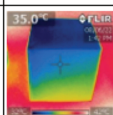
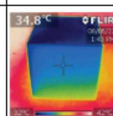
Table 7. Thermal test result (Day 2), 8/6/ 2022
(Outdoor Temperature: 31 °C, 1.00pm)

Time	Conventional Concrete			Transparent Concrete (290 optical Fiber)			Transparent Concrete (560 optical Fiber)		
	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)
0 minutes	 26.9	27.1	0.2	 26.6	25.7	0.9	 26.4	25.5	0.9
15 minutes	 31.6	30.5	1.1	 31.0	30.1	0.9	 30.7	29.3	1.4
30 minutes	 34.5	34.0	0.5	 34.1	33.7	0.4	 33.9	32.6	0.3
Average Temperature	31.00	30.5	0.6	36.10	29.8	0.73	34.93	29.1	0.86

(Source: Author)

Table 8. Thermal Test Result (Day 3), 9/6/ 2022 (Outdoor Temperature: 32 °C, 1.00pm)

Time	Conventional Concrete			Transparent Concrete (290 optical Fiber)			Transparent Concrete (560 optical Fiber)		
	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)	Thermal Infrared image/ Outdoor Surface Temperature (°C)	Indoor Surface Temperature (°C)	Temperature Difference (°C)
0 minutes	 30.2	29.6	0.6	 29.3	28.5	0.8	 29.0	28.3	0.7
15 minutes	 34.5	33.8	0.7	 34.1	33.2	0.9	 33.8	32.7	1.1
30 minutes	 35.5	34.9	0.6	 35.0	34.2	0.8	 34.8	33.7	1.1
Average Temperature	33.40	32.8	0.63	32.80	32.0	0.83	32.53	31.6	0.96
Total Average Temperature	33.589	32.9	0.72	33.156	32.3	0.86	32.600	31.7	0.94

(Source: Author)

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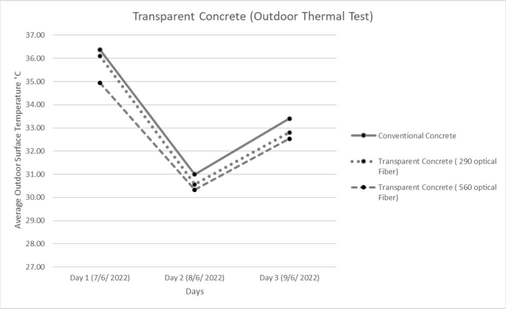

Figure 10. Total Average Outdoor Surface Temperature of Transparent Concrete

(Source: Author)

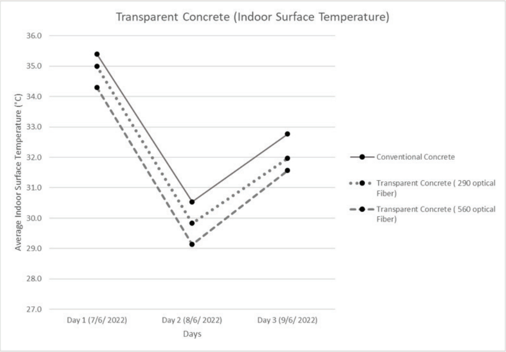

Figure 11. Total Average Indoor Surface Temperature of Transparent Concret

(Source: Author)

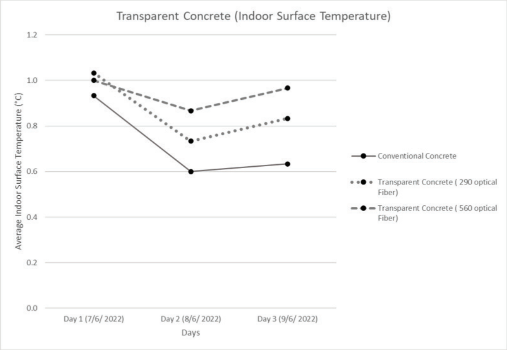

Figure 12. Total Average Temperature different of Transparent Concrete

(Source: Author)

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Visual effects of transparent Concrete

Figure 13 shows that the light transmission is clearly identified on transparent concrete. The surface area of the whole concrete increases as the diameter of the poly methyl methacrylate (PMMA) fibre optic increases, and the light transmission increases as well. The visual shadow effect on object may varies according to the brightness of light source. The author also designed variety of arrangement of poly methyl methacrylate (PMMA) fibre optic to indicate the flexibility of transparent concrete as shown in Figure 13.

Figure 13. Visual Effect of Transparent Concrete

(Source: Author)

CONCLUSION

Based on this study, fiberglass chopped strands in concrete mixture able to improve the constructability, workability to the point where it could be poured firmly into the mould during the process of transparent concrete. This experiment selects fibre optic as primary material to study the effectiveness on daylighting, thermal and visual effect. The effects of different proportions of poly methyl methacrylate (PMMA) on light transmission and thermal performance are discussed. The concrete samples were placed below sunlight to analyse the light transmission and thermal conductivity of conventional concrete and concrete with fibre optic.

In conclusion, transparent concrete has a distinct light transmittance property that can maximise daylight usage during the daytime. At night the transparent concrete can be visually attractive and welcoming for buildings, furniture, and hardscapes. This study shows the improvement in light transmittance after the percentage and number of optical fibre usage increases. The result of light illuminance shows that transparent concrete is suitable to apply as exterior panel or interior panel to receive sufficientdaylight into a space. Moreover, it also indicates that the thermal performance was improved using transparent concrete compared to conventional concrete. It shows the lower temperature of the concrete as the number of poly methyl methacrylate (PMMA) fibre optic increases. It indicates that the use of fibre optic improved the thermal conductivity of the concrete.

The main contribution of this experiment indicates that the higher usage of poly methyl methacrylate (PMMA) fibre optic allows more daylighting and lower the thermal conductivity and heat gain. It also changes the perception of more light received, the more the heat conductivity increases. The study can highlight solutions on thermal comfort and high energy usage issues. It also delivers the potential of transparent concrete to increase the energy efficiency of a building. However, there is limitation of data for duration to measure thermal heat loss because of the local weather conditions which influence the temperature of the concrete. Therefore, further studies can explore the study of transparent concrete on thermal heat loss in longer duration which include day and night temperature. The study may benefit on lower usage of electricity and air-conditioning which helps to reduce energy consumption especially during daytime.

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AUTHOR CONTRIBUTIONS

All authors contributed to the development of the research, the field measurement studies, and the write-up. The data and tabulation were undertaken by the researchers involved in Universiti Sains Malaysia. All authors have read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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