EXPERIMENTAL STUDY ON THE PERMEABILITY OF LIGHT TRANSMITTING CONCRETE USING OPTICAL FIBERS AND TRANSPARENT POLYMER RODS

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Abstract - This study focuses on analyzing the permeability of light transmitting concrete (LTC) using plastic optical fibers (POF) and transparent Polymethyl methacrylate (PMMA) rods with varying diameters and content within the concrete. Experiments were conducted on both thin plate samples to test water penetration time, water absorption and permeability, as well as on cylindrical samples to assess the waterproof grade of the material. Subsequently, a waterproofing layer using a Siloxane-based material layer was applied to the concrete samples. The experimental results shown that using small-diameter optical fibers results in lower permeability compared to using large-diameter PMMA rods. This is because the bond between the optical fibers and the concrete is better than that when using PMMA rods. Additionally, increasing the content of PMMA rods significantly increased the water permeability of the material.

Key words - Light transmitting concrete; PMMA; optical fiber; permeable; waterproofing grade; waterproofing materials

1. Introduction

In recent years, light transmitting concrete (LTC) has had the potential and unique building material in the construction industry [1]. The structure of LTC is shown in Figure 1, created by arranging light transmitting materials such as POF, transparent polymer rods or glass to create continuous light transmission lines inside the concrete [1-3]. The combination of light transmission and the load bearing properties of concrete has opened up new solutions, allowing architects and civil engineers to create unique and environmentally friendly buildings. Changing the content of transmission materials inside the concrete can help adjust and optimize the amount of light shining directly from the outside into the buildings, creating living and working spaces with just enough light without the need for a combined curtain system. In addition, the insulation properties of based concrete materials are higher than conventional lighting solutions using tempered glass or transparent plastic, helping this material reduce the heat radiation of sunlight and buildings save energy in air conditioning in spaces while still being able to effectively get natural light. With the above performances, light-transmitting concrete is considered a new generation innovative material with great potential for many diverse applications in architectural works, tunnels, or in the development of smart road surface solutions capable of displaying traffic signals.

Several studies on LTC have been conducted in recent years. Chiew et al. [2] analyzed the economic characteristics of LTC, indicating that although the initial production cost is higher than that of ordinary concrete or light transmitting materials such as tempered glass or transparent plastics, the long-term energy-saving effect can offset these costs and contribute significantly to the reduction of global warming. In addition, the unique architectural effects brought by translucent concrete can help increase the attractiveness of buildings, creating aesthetics, tourism and other commercial values. Studies [3-13] analyzed the mechanical properties of LTC with different mix proportions, achieving compressive strength from 20÷80MPa. These studies mainly used optical fibers with diameters of 0.5÷1.5 mm as light transmitting materials, and arranged with a volume content of less than 10% inside the concrete. The results of most studies showed that increasing the proportion of POF would increase the light transmission but significantly reduce the mechanical strength of LTC. This is because increasing the POF content would increase the workability requirement of the concrete mixture to be able to filling up the narrow gaps between the optical fibers. When the workability is not reached, gaps may form around the optical fiber and reduce the strength of the light transmitting. In addition, because the light transmitting material is made of POF with low elastic modulus, it does not participate in the load-bearing capacity of the LTC at the same time. Therefore, the arrangement of these materials with high content inside the concrete will reduce the effective load-bearing cross-section of the concrete, reducing the strength of the LTC.

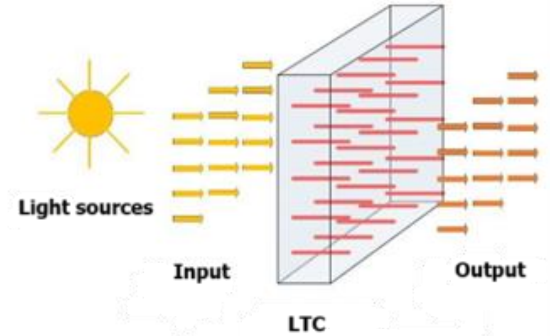


Figure 1. *Basic principle of LTC*

Recently, the research of Nam et al [14] has successfully developed LTC with a transparent material content of up to 30% while still ensuring the strength of the concrete at over 40MPa, higher than that of ordinary concrete, suitable for most applications in common civil works. The core idea of this research is to use transparent plastic rods made of Polymerthyl methacrylate (PMMA) with a diameter of 5÷20mm, larger than the usual POF with a diameter of less than 2.0mm. By this approach, the research team can increase the clear distance between light transmitting materials with the same volume content arranged inside the concrete, thereby helping to reduce the workability requirements of the fresh concrete mixture, ensuring the filling of the concrete mixture between the light transmitting materials.

Although the above studies have clarified the basic properties of LTC including light transmission, mechanical strength and economy, there has been almost no research focusing on analyzing the permeability of this material, especially when the translucent material is used with a high content of over 10% inside the concrete. Meanwhile, when constructing LTC in structures such as the outside walls of buildings, facade or pavement concrete materials for smart traffic signal solutions, understanding the permeability properties of LTC is extremely important, helping Civil Engineers to come up with suitable waterproofing solutions for specified project.

Therefore, this study focused on analyzing the permeability of LTC using POF and transparent PMMA rods with different diameters and contents. Specifically, POF with a diameter of 2.0mm, and PMMA rods with diameters of 10, 15, 20mm were used. These materials were arranged inside the concrete with ultra-high volume contents, specifically 10, 20 and 30% inside the concrete. The permeability test of LTC was performed on both thin plate specimens to check the water penetration time, water absorption and penetrated through the specimens as well as check the waterproofing grade of the material on cylinder specimens. After discussing the results of the permeability test of the LTC, a method using a Siloxanes-based waterproofing material was proposed and tested by a verification experiment.

2. Materials and experimental methods

2.1. Mix proportions

The key to developing LTC with highly light transmission and mechical strength is to ensure the workability of the fresh concrete mix and the high design strength of the harden concrete. Crushed stone and coarse sand cannot be used in the concrete mix compositions because particles diameter is larger than 1/2 of the clear distance between the translucent materials used in high content in LTC. Therefore, an effective approach is to use the mixed design principle of activated fine-grained concrete [15, 16]. This aim uses a combination of fine sand and activated mineral powder such as ground-granulated blast-furnace slag (GGBS) and fly ash (FA) to replace part of the cement amount. The spherical particle structure of FA helps to reduce the amount of water used while improving the workability of the concrete mix [17, 18]. In addition, the pozzolanic reaction of GGBS produces Calcium Silicate Hydrate (C-S-H), which increases the compressive strength at long ages [19]. Furthermore, replacing cement with these industrial waste products also meets the criteria of environmentally friendly materials of LTC. To minimize the amount of water used to increase the design strength of concrete while still ensuring workability, Polycarboxylate Ether (PCE) superplasticizers are chemical admixtures, high water reduction capacity that improve the flowability, and strength of concrete.

(a) Sand *(b) GGBS* *(c) FA*

Figure 2. *Fine aggregates and activated mineral binders*

Ordinary Portland Cement (OPC) PC40 from Song Gianh Cement Factory was chosen for doing all tests, conforming to TCVN 2682:2009 [4]. S95 is GGBS which a product of Hoa Phat Complex Steel Factory, Quang Ngai province, meeting TCVN 11586:2016 [5], type F fly ash from Vinh Tan 2 Thermal Power Plant in Ninh Thuan province, Vietnam, was utilized as supplementary cementitious materials. Table 1 shows detailed chemical composition of OPC, GGBS and FA. The natural fine sand taken from Phong Dien district, Thua Thien Hue province, predominantly composed of quartz (SiO_2 >98%). Other parameters of sand include density of 2.43kg/m^3, bulk density of 1430kg/m^3. The results of sand particle size test are shown in Figure 3, with sand particle size in the sieve size range 0.15 ÷ 0.6mm, modulus 1.58.

Table 1. *Chemical composition of OPC, GGBS, FA*

Chemical composition (%)	OPC	GGBS	FA
SiO_2	21.5	35.77	68.50
Al_2O_3	5.45	13.02	11.90
CaO	61.5	40.24	1.16
MgO	1.9	7.74	0.51
SO_3	2.3	0.18	0.31
Fe_2O_3	-	0.8	10.3
Na_2O	-	0.22	0.14
K_2O	-	0.89	3.12
L.O.I	2.3	0.11	3.21

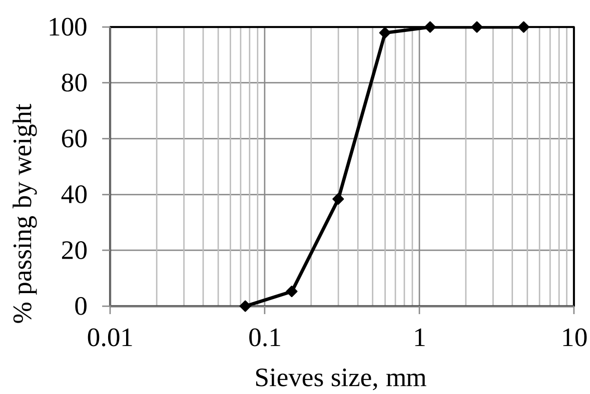


Figure 3. *Curve of particle gradation fine sand*

Mix proportions for 1m^3 concrete mixture are presented as Table 2. The concrete mix is designed to archive target strength of 80MPa in the absence of light-transmitting materials. The optimal replacement ratio of OPC by FA and GGBS carried out in Huynh Phuong Nam et al. previous study [12, 13], namely 15% for FA and 30% for GGBS. Lotus-301M liquid admixture superplasticizer of Hoa Sen Chemical JSC was used to enhance the flowability of fresh concrete. The dosage of superplasticizer was adjusted and selected according to Table 2 based on the flow table test to ensure the workability of fresh concrete in the mold with the highest OPC and PMMA content, facilitating the compaction of fresh concrete mixture into the narrow gaps between the light-transmitting materials. The flow table test values were observed and measured higher than 800mm.

Table 2. *Mix proportions for 1m^3 concrete mixture*

OPC, kg	GGBS, kg	FA, kg	Sand, kg	Adm, ltrs	Water, ltrs	W/B, %
495	270	135	1183	6.3	240	0.27

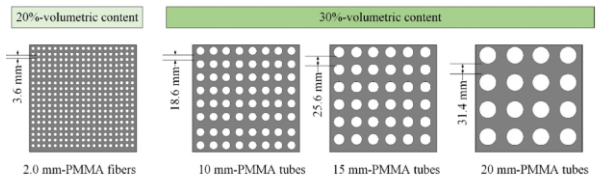
2.2. Experimental parameters and specimen preparation

The experimental parameters for the LTC specimens were the diameter and content of the light-transmitting material inside the concrete. The light-transmitting materials used in the study included POF 2.0mm diameter and transparent PMMA rods with three diameters of 10, 15, and 20mm. The POF used were products of Tongling Optical Fiber Technology Co., Ltd., and were arranged with volumetric contents of 10% and 20% inside the concrete. The PMMA rods were provided by Dongguan Polymer Company, and were arranged with contents of 10%, 20%, and 30% inside the concrete. In addition, to increase the bond between the PMMA bar and the concrete base, in addition to the case of using bars with smooth surfaces, the case of machining to create surface threads is also used for PMMA bars with diameters of 15 and 20mm. Table 3 shows the types of specimens used in the study and the corresponding specimen symbols. Note that the specimen symbols are assigned after the character names corresponding to the results of the corresponding test items including ‘T’ for water penetration time, ‘P’ for water penetration; ‘W’ for waterproofing grade.

Table 3. *Experimental parameters and sample symbols*

Sample type	Sample
Concrete base (no light-transmitting materials)	0
Fiber 2mm optical, 10 % content	F2-10
Fiber 2mm optical, 20% content	F2-20
10mm smooth rod, 30 % content	T10-30
15mm smooth rod, 30 % content	T15-30
15mm rod, surface thread surface, 10 % content	T15R-10
15mm rod, surface thread surface, 20% content	T15R-20
15mm rod, surface thread surface, 30% content	T15R-30
20mm rod, surface thread surface, 30% content	T20R-30

Figure 4(a) shows the spacing between the translucent materials when arranged with a volume content of 20% for POF and 30% for PMMA rod. Although the volume content remains the same, the use of larger diameter PMMA can significantly increase the clear spacing between the rods, thereby making it easier for the fresh concrete mixture to fill the narrow gaps. Figure 4(b) shows the formwork arrangement in the case of using POF (left), 10mm diameter plain PMMA (middle) and 20mm diameter surface-threaded (right). In addition, Figure 4(c) shows the fresh concrete mixture when poured into the formwork. It can be seen that the flowability of the concrete mixture is suitable to ensure that the concrete mixture can fully filled.



(a) Light transmission material distance

(b) Formwork regime create sample

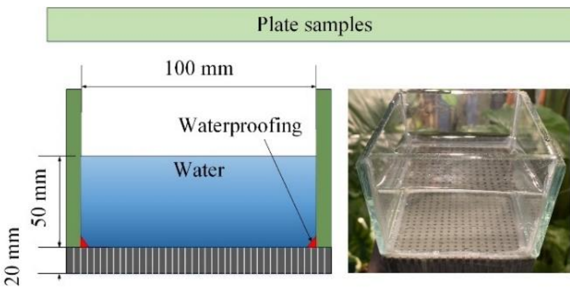
(c) Pour calf tone enter board mold

Figure 4. *LTC specimens preparation*

2.3. Test methods

There are two types of tests used to investigate the permeability of LTC, including (i) water penetration test for thin plate specimens, and (ii) waterproofing grade test for cylindrical specimens. Water penetration test was carried out according to TCVN 4313:1995 [22] with a 24-hour water penetration observation time on plate samples of size 100×100×20mm. The test samples consisted of concrete slabs fixed with glass panels on the side walls, and the gaps were connected with water-resistant silicone sealant. The samples were dried, then filled with water to a height of 50mm for the samples as shown in Figure 5(a). Observations on the bottom surface of the samples were carried out at intervals of 2 hours up to 24 hours to determine the water penetration time for each type of sample. During this process, the samples were sealed to prevent water evaporation due to temperature. After continuous observation for 24 hours, the samples containing the remaining water were weighed and the amount of water absorbed and penetrated by each sample in 24 hours was determined.

The water tightness test was performed on a cylindrical concrete specimens with a diameter of 150mm and a height of 150mm for each case of POF and PMMA. The testing procedure was carried out according to TCVN 3116:2022 [23]. The specimens was placed in the test mold of the permeability testing machine and the water pressure was increased at each level, starting from level 0.2MPa. The pressure increase time was from 1 to 5 minutes and the pressure level was maintained for 16 hours. Observe the open surface of the specimens when water seeps in the form of drops or moisture, then close the water pressure valve and stop the test. The waterproofing grade of each type of specimens is determined by the maximum water pressure level at which the specimens is not penetrated by water. In addition, electron microscopy experiments were also performed on the samples to clarify the microstructure of the translucent concrete, especially the bond between optical fibers or PMMA bars and concrete, thereby investigating the cause of the permeability difference between concrete specimens. The experimental procedures and methods were similar to previous studies by the authors [12-14].



(a) Water penetration test

(b) Watermark test

Figure 5. *Permeable tests*

3. Results and discussions

3.1. Surface characteristics and compressive strength

The mechanical strength and light transmission properties for different light spectra have been presented in the authors' previous study. [6]. This study focuses on the investigate of the permeability capacity of LTC, so the experimental results are not represented in detail in this study. However, because this is a new innovative concrete that has not been published much in other domestic studies, this study presents a summary of the results of the surface image as well as the results of the compressive strength of LTC.

First, the surfaces of several specimens with different fiber contents and diameters or PMMA are shown in Figure 6. It can be observed that all the specimens fabricated have uniformly smooth surfaces without significant voids. This demonstrates the workability of the concrete mixture to compact the fresh concrete mixtures tightly between the POF contents of up to 20% and the PMMA of up to 30%. In addition, there is a noticeable difference in the light transmission effect between the concrete specimens using different diameters of POF and PMMA. The closer spacing of the POF allows the light to be evenly distributed over the concrete surface, while the light tends to be concentrated at the rod locations for the concrete specimens using larger diameter PMMA.

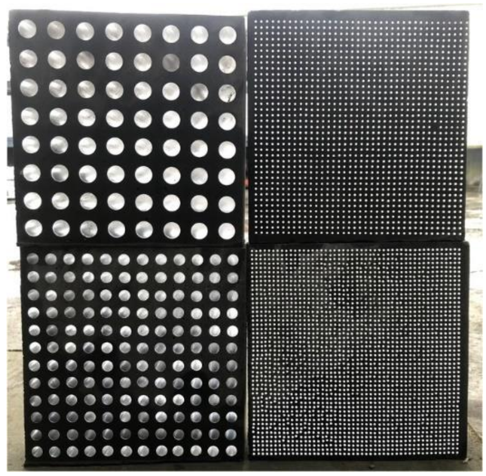


Figure 6. *LTC surfaces*

Table 4. *Average compressive strength of LTC*

Sample type	Ave. Compressive strength, MPa
Control (Concrete based)	88.3
POF 2mm, 10 % content	69.1
POF 2mm, 20% content	61.9
10mm smooth, 30 % content	43.1
15mm smooth, 30 % content	46.6
15mm bar, surface thread surface, 10 % content	59.9
15mm bar, surface thread surface, 20 % content	51.8
15mm bar, surface thread surface, 30 % content	41.8
20mm bar, surface thread surface, 30 % content	44.6

Table 4 shows the results of the average compressive strength test of the LTC specimens at 28 days of age. It can be seen that the strength of the base concrete reached 88.3 MPa, higher than the target design strength of 80MPa. However, when POF or PMMA with high content were used, the compressive strength of the concrete specimens decreased significantly. Table 4 also shows that the higher the content of the translucent material, the lower the compressive strength of the concrete specimens. This is because translucent materials including POF and PMMA have very low elastic modulus, so they do not participate in the load-bearing capacity of the base concrete. That is, the larger the translucent material occupancy, the lower the effective bearing cross-section of the concrete, leading to a decrease in the compressive strength of the specimens. On the other hand, the results in Table 4 also show that the compressive strength of LTC specimens using POF is higher than that of those using PMMA. This may be due to the fact that the use of PMMA causes stress concentration in the remaining cross-section of the concrete, thus causing a sharp decrease in the compressive strength of the material. However, the results of Table 4 show that all LTC specimens compressive strength above 40MPa, which is higher than that of conventional concrete. Therefore, the LTC developed in the study meets most applications in civil and infrastructure works.

3.2. Water penetration time

The results of the water penetration test of concrete slab specimens under the pressure of a 50mm high water level are shown in Figure 7. The horizontal axis represents the symbol of the specimens while the vertical axis represents the time when water drops first appeared under the specimens. Note that observations were made every 2 hours from the start of the test.

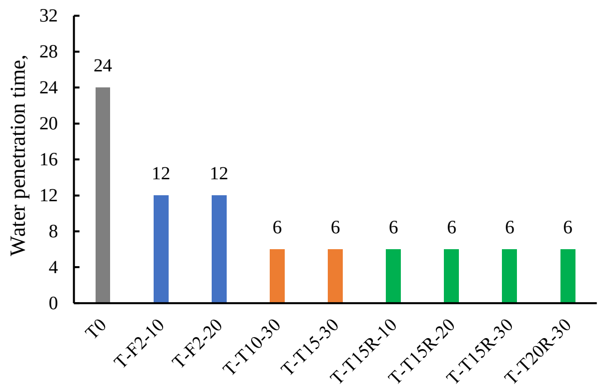


Figure 7. *Water penetration test results of LTC*

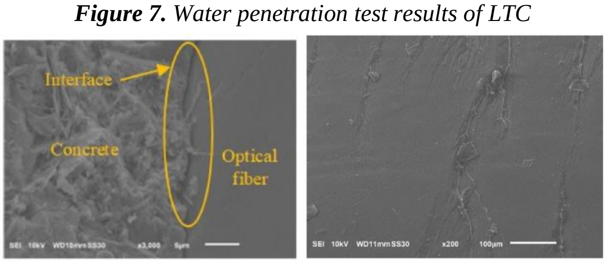


Figure 8. *Observation of LTC microstructure surface*

The results in Figure 7 show that no water drops appeared under the Control (T0) after 24 hours of observation. This proves that the base concrete without light-transmitting material has a solid structure, not allowing water to penetrate under the condition of a water column pressure of 50mm within 24 hours. Meanwhile, water drops began to appear under the samples using POF 10% (T-F2-10) and 20 % (T-F2-20) after 12 hours of observation and appeared for all samples using PMMA after 6 hours of observation. That is, with the same concrete mix ratio, water penetration increases significantly when light-transmitting materials are arranged inside the concrete.

On the other hand, according to the analysis of the clear distance in Figure 4(a), it is clear that the use of large diameter PMMA will increase the distance between the light-transmitting materials, making it easier for the fresh concrete mixture to be filling up the formwork. Thus, increasing the density of the concrete in this case compared to when using POF small diameter. However, the results in Figure 7 show that the samples using large diameter PMMA give earlier water penetration times than those using POF small diameter. It means that this difference may not be due to the difference in the density of the microstructure of the base concrete itself, but mainly due to the gap between the light-transmitting materials and the surrounding concrete.

To clarify the above explanation, Figure 8 shows the microstructural observation results for the POF surface and the surface of the smooth PMMA rods from LTC. It can be seen that traces of concrete are still attached to the POF surface on the left, while there are almost no traces on the PMMA rod surface as shown on the right. In other words, the bond between the POF and the base concrete may be better than the case of using large diameter PMMA. This may be the main reason for the difference in water penetration time between these two types of specimens as shown in Figure 7.

3.3. Water absorption test

The results in Figure 7 do not clearly show the influence of the content, diameter and surface profile of the thread on the PMMA on the water permeability of the LTC. Although the water droplets appear at the same time, the amount of water that penetrates can be different between the test specimens. Therefore, Figure 9 shows this influence through the calculation of the percentage of water loss compared to the initial water amount after 24 hours of measurement for all specimens. Since the water containers of the specimens were sealed during the measurement, this water loss can be considered as the sum of the amount of water absorbed into the specimen and the amount of water that penetrated the specimen.

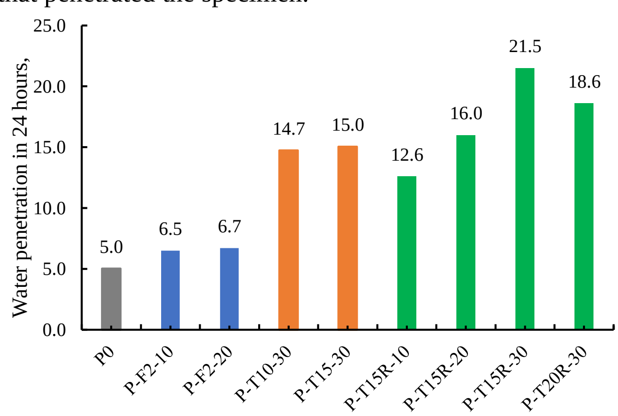
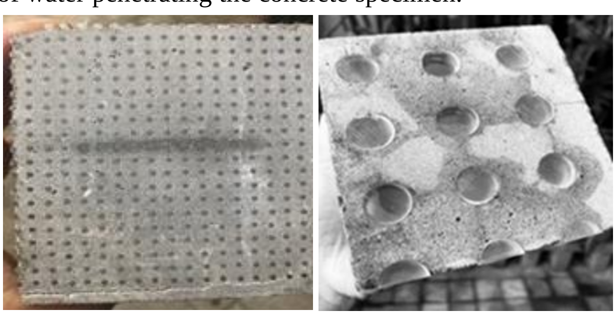


Figure 9. *Water penetration test results*

Figure 9 shows that the water loss of P0 (Control specimen) is 5%. Since no water drops are observed at the bottom of the sample, this water loss can be considered as the amount of water absorbed into the microstructure of P0. On the other hand, there is no significant difference in the amount of water loss between the samples with 10% (P-F2-10) and 20% (P-F2-20). Since the polymer material used to make the fiber itself is considered a water-resistant material, that is, it almost does not absorb water, POF the higher, the smaller the amount of water absorbed into the sample, reducing the amount of water loss during test. On the contrary, increasing the POF increases the internal transition zone between the fiber and the concrete based, increasing the water permeability, thereby increasing the amount of water loss. Because these two effects neutralize each other, the difference in water loss between the two types of samples with POF of 10 and 20% is not as large as the result in Figure 9.

For the case of using smooth surface PMMA, there is no obvious difference between the samples using 10mm diameter (P-T10-30) and 15mm diameter (P-T15-30) with the same 30% content, showing that the bar diameter does not greatly affect the amount of water absorbed and penetrated by the concrete sample. For the case of using threaded surface PMMA with the same diameter of 15 mm, increasing the PMMA content from 10% (P-T15R-10), 20% (P-T15R-20) to 30% (P-T15R-30) significantly increases the amount of water loss. Although PMMA is a non-absorbent material, increasing the content can reduce the amount of water absorbed into the concrete specimens, but it also significantly increases the gaps between the PMMA and the concrete base, thereby increasing the amount of water penetrating the specimen. This results in a higher amount of water loss when increasing the PMMA content as shown in Figure 9.

In addition, the results in Figure 9 show that using threaded PMMA (P-T15R-30) gives a higher amount of water loss than smooth bars (P-T15-30). This may be due to the threaded grooves having a width and depth of about 1mm, which will create narrow areas that are difficult to fill. Therefore, gaps will be created, increasing the amount of water penetrating the concrete specimen.



(a) LTC used POF 2mm *(b) LTC used thread PMMA*

Figure 10. *Bottom surface of samples after 24 hours in water penetration test*

On the other hand, Figure 10 shows the underside of the concrete specimen using POF and using 15mm diameter threaded PMMA after 24 hours of water penetration test. Water streaks can be observed in the middle of the fiber-optic sample in Figure 10(a). This may be due to segregation between the two concrete layers during poured. Specifically, when pouring concrete into half of the formwork, the samples were placed on the vibrating table, then the second layer of concrete was poured. This may cause micro-cracks to appear between the two layers of concrete, concentrating the water streaks as shown in Figure 10(a). This result shows that the need to pay attention to the construction work. Moreover, Figure 10(b) shows water streaks appearing around the PMMA and spreading to the surrounding concrete areas. This is evidence that the gap between the PMMA and the concrete base is the main cause of increased water permeability of concrete samples using PMMA.

3.4. Waterproofing grade

Waterproofing grade was performed by watermark method according to TCVN 3116:2022 [7]. Control (W0) and LTC specimens were subjected to various levels of water pressure for 16 hours in the mold, starting from 0.2MPa and the test results are shown in Table 7. Table 7 shows that the W0 and W-F2-10 & W-F2-20 can withstand the highest water pressure, up to 1.2MPa, equivalent to waterproof grade W12, while the remaining samples using PMMA only achieved W2 grade. This result is quite similar to the results in sections 3.2 and 3.3.

Table 5. *Waterproofing grade test results*

Sample	Maximum water pressure, MPa	Waterproofing grade
W0	1.2	W12
W-F2-10	1.2	W12
W-F2- 20	1.2	W12
W-T10-30	0.2	W2
W-T10-30	0.2	W2
W-T15R-10	0.2	W2
W-T15R-20	0.2	W2
W-T15R-30	0.2	W2
W-T20R-30	0.2	W2

(a) W-F2-10 *(b) W-T15R-30*

Figure 11. *Waterproofing test on LTC*

Figure 11 shows the watermark that non-appeared on W-F2 and appeared on PMMA 15mm diameter with threaded surface. Because the amount of water seeping through the POF specimens is very small, the seepage streaks are not obvious. On the contrary, the water streaks appear starting from the position around the PMMA in the sample in Figure 11(b). This result is completely consistent with the observation in Figure 10(b) in Section 3.3. Thus, it can be concluded that the water permeability of the LTC using PMMA is higher than that of those used POF. This is mainly due to the micro-gap between the PMMA and the base concrete.

4. Proposed waterproofing material solutions

From the experimental results in section 3, it can be seen that increasing the waterproofing properties of LTC, especially for samples using PMMA, is extremely necessary when this material is used in the covering structures of civil works (i.e external walls, façade, …). To increase the waterproofing properties without affecting the light transmission capacity of LTC, the study used Sikagard 700S apply on the surface of LTC. This is a one part repellent impregnation for absorbent cementitious substrates.

Table 6. *Typical properties of Sikagard 700S*

Chemical base	Silanes/Siloxanes blend in organic solvent
Appearance / Color	Colorless liquid
Density	~ 0.08 kg/liter (20^{o}C)
Consumption	0.50 ÷ 1.25 liters /m^2

Method statements of Sikagard ® 700 S provided by Supplier. Substrate preparation free of dust, oil, efflorescence and dry. Sikagard 700S applied by using low pressure spray, brush or roller. Apply subsequent coats when first layer still wet. After 2 days of applied Sikagard 700S, to verify the effectiveness of the waterproofing layer, the study re-conducted the waterproofng test on LTC used PMMA with diameters of 10, 15, 20mm, 30% content. The results show that the low waterproofing grade W2 has increased to W12, equal to the W0 and W-F2-10. This shows that the Sikagard 700S layer is in liquid, transparent form, penetrating into the concrete surface, creating a water-resistant mechanism, preventing capillary seepage and mold on the surface of the concrete sample. The results show that the use of a waterproofing layer is useful in preventing the permeability of LTC while still ensuring the light transmission ability of its.

(a) Before Sikagard 700S applied　*(b) After Sikagard 700S applied*

Figure 12. *LTC non-use & used Sikagard 700S*

Table 7. *Waterproofing test on LTC applied Sikagard 700S*

Sample	Maximum water pressure, MPa	Waterproofing grade
W-T10-30	1.2	W12
W-T15-30	1.2	W12
W-T15R-30	1.2	W12
W-T20R-30	1.2	W12

5. Conclusion

This study focused on the permeability of LTC using POF and PMMA with different diameters and contents and proposal waterproofing solutions effectively. The experiments were carried out on both thin plate specimens to test the water penetration time, water absorption, as well as on cylinder specimens to test the waterproofing grade of the material. Some of the main results obtained from the study are as follows:

i. The mix proportions concrete is appropriate, ensuring simultaneously (i) workability for the concrete to fill the gaps between the light-transmitting materials, (ii) high mechanical strength above 80MPa, and (iii) solid structure to limit the phenomenon of water seepage through the capillaries of the base concrete.

ii. Permeability is shown by the results of water penetration time measurement, the amount of water penetration of LTC using PMMA is higher than that of LTC using POF 2mm. The water penetration streaks are mainly concentrated in the gap between PMMA and surrounding concrete. This phenomenon proves that the bond between PMMA and surrounding concrete is the root cause of water penetration.

iii. The water permeability of LTC increases in case the increase in the content of PMMA. On the other hand, the processing of the thread surface of PMMA can create gaps between the rods and the base concrete, thus increasing the water permeability.

iv. The waterproof grade is expressed by the water pressure at the time of the appearance of the watermark of LTC used PMMA, which is W2, while for Control and LTC used POF, it is W12. Therefore, when manufacturing LTC uses PMMA, the waterproofing layer is mandatory. Using a transparent, liquid waterproofing layer that penetrates the concrete surface creates a water-resistant mechanism, prevents capillary seepage and mold on the surface of the concrete sample, and still ensures the light transmission of the concrete samples.

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