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State-of-the-art developments in light transmitting concrete

Shwan H. Said

Department of Environment and Pollution Engineering, Technical College in Kirkuk, Northern Technical University, Mosul, Iraq

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ABSTRACT

As the population grows rapidly, many tall buildings have been established in crowded areas creating huge obstacles for transmitting the natural sunlight into these buildings. After numerous experiments conducted by engineers, to imbue new and modern features of concrete, an innovative, smart and novel construction material called "light transmitting concrete" (LiTraCon) has emerged in the last decade, manufactured by embedding optical fibers in concrete. The new material is characterized by allowing the light to pass through itself. LiTraCon has smart properties such as energy saving, decorative and aesthetic appearance, and enhancing the daylight indoor quality of buildings. The latest developments attained by researchers are presented and discussed in this article such as the impact of optical fibers on the mechanical properties, durability and the light transmittance ability of LiTraCon. Results showed that the mechanical strength lowered within acceptable limits. The optical fibers have an adverse effect on the durability. Besides, increasing the optical fiber content up to 5–6%, or increasing the fiber diameter up to 2 mm, enhanced the optical transmittance ability with acceptable mechanical properties of LiTraCon. Finally, using regularly aligned optical fibers is better than using random fibers to obtain better mechanical strength. However, regularly aligned optical fibers haven't substantially shown better transmittance ability as compared to random alignment of fibers.

Selection and peer-review under responsibility of the scientific committee of the 10th International Conference on Key Engineering Materials 2020.

1. Introduction

Light transmitting concrete (LiTraCon), or transparent concrete, or translucent concrete (TC) is one of the most currently emerging sustainable and green construction material discovered by Aron Losonczi, the Hungarian architect, who produced the first LiTraCon block in 2003. The main concept is by placing optical fibers uniformly in horizontal form inside the mould before the casting process of concrete, producing basic construction units of LiTraCon, such as blocks or panels. Different types of optical fiber were used in these applications such as Polymethylmethacrylate (PMMA) as polymer fibers [1,2] or plastic optical fiber (POF), and glass optical fiber (GOF). Its function as a guide to the light wave transmits from one end of the fiber to the other.

It was demonstrated that 50% of daylight should be transmitted into the green buildings, according to Indian Green Building Council, and this condition cannot be attained without the fabrication of LiTraCon [3]. The novel construction material is essential for architectural purposes, decorating the interior design of building, i.e. in ceilings, partitions and instead of windows to transmit the light, in walls and facades of building, for illumination of tunnels and dark subway stations, used for speed bumps, and lane markings in highways [3–5].

In this review study, important parameters, influencing the LiTraCon mix design, are demonstrated and presented through latest research. Also, the impact of optical fiber content and diameter on the mechanical properties, durability and light transmittance ability of LiTraCon were discussed. The research process in this field is uninterrupted to promote the construction sustainability and green building requirements. Fig. 1 illustrates some applications of LiTraCon.

2. Mix design of light transmitting concrete (LiTraCon)

2.1. Components

The main components predominantly consisted of Portland cement, fine aggregate (sand) with max size particles ranges 0.6–4.75 mm, coarse aggregate (gravel) with max size particles ranges 10–12 mm, optical fibers, and water. In addition, distance between

E-mail address: shwan@ntu.edu.iq

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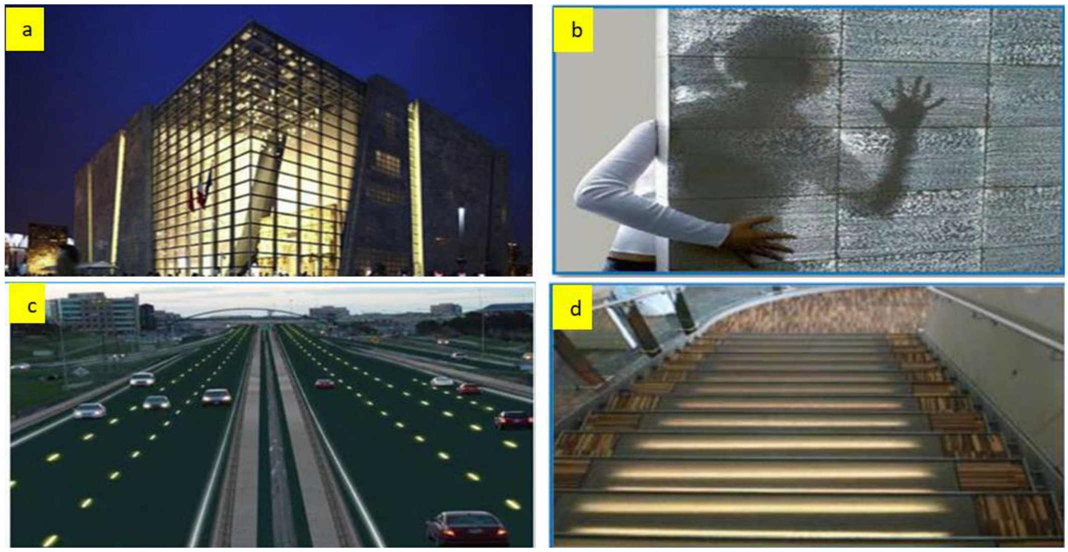

Fig. 1. Applications of LiTraCoin in illumination of: (a) walls (b) partitions (c) lane markings in highways (d) stair case [2,6].

the optical fibers arranged inside mould specifies the nominal size of coarse aggregate [7].

Instead of optical fibers, some LiTraCons consisting of other types of cheaper light-guiding materials such as waste glasses [8,9], glass rods [10], acrylic rods [11], epoxy resin rods [12], and special plastic resins (such as in Ilight transparent cement mortar) [13]. Some authors used some types of additives among the components to promote the properties of LiTraCon such as superplasticizer, silica fume, fly ash, GGBS.

Optical fibers should be placed parallel to each other in the mould and should be tightened at both ends, and overstressed fibers should be avoided.

2.2. Optical fiber spacing

Due to the short distance between the optical fibers in the mould, and difficulties of obtaining good compaction and homogeneity of mixture between optical fibers, authors prefer to promote the consistency and workability of mixture by following some mix procedures, such as excluding the gravel from the ingredients producing a mix called "light transmitting cement mortar", using superplasticizers, or highly fine grained binders as cement replacement, or producing self-compacting concrete. Moreover, short distances between the installed parallel fibers lead the micro cracks to propagate considerably [14]. As a result, some authors used 10% silica fume as partial replacement of cement in LiTraCon [14–17] to enhance the strength characteristics, avoid segregation, to increase cohesion and, to increase adhesion at fiber/matrix interface.

2.3. Self-compacting LiTraCon

Self-compacting concrete (SCC) is a good choice for the fabrication of LiTraCon to avoid the concerns of missing the optical fibers alignment via concrete vibrators, as the SCC gets compacted under its own weight [18]. In addition, Salih et al. (2014) [19] showed that the fabrication of self- compacting mortar is very convenient to prepare a translucent concrete due to its homogeneity which facilitates casting and finishing. On the other hand, Spiesz et al. (2016) [8] and, Pagliolico et al. (2015) [9] produced translucent concrete panels consisting of waste glass particles as a replacement to the sand and gravel, by preparing white cement self-compacting concrete by using finely grained materials such as fly ash or GGBS.

2.4. Translucent concrete and translucent cement mortar

It was shown via a comparative experimental investigation on translucent concrete and translucent cement mortar, that the translucent cement mortar is around 67% more efficient than the translucent concrete [20,21], and in another experiment is around 8–20% more efficient [22], in light transmission. Fig. 2 illustrates the preparation and placing of POF in the mould.

3. The effectiveness of optical fibers on the mechanical properties of LiTraCon

3.1. Optical fiber content

Regarding LiTraCon, most experimental work demonstrated there is a reduction in compressive strength with increasing optical fiber content of LiTraCon [3,10,12,20,22–25], or a combined reduction in compressive and flexural strength as optical fiber content increases [1,2,5,15,16,17,19], as indicated in Table 1. Besides, most researchers revealed that the reduction in the LiTraCon compressive strength ranges between 3 and 11%, which is insignificant, whereas other researchers have shown that the reduction is around 16 to 30%. Moreover, the results have shown a reduction in flexural strength of around 3 to 21% whereas few results indicated a reduction of about 17–40% in flexural strength.

Other researchers revealed that there is an increase in compressive strength of LiTraCon [14,26,27], or a combined increase in compressive and flexural strength, with increasing optical fiber content [4,28,29].

Some results confirmed that the compressive strength increases with increasing the optical fibers until 3% [5,27], or until 4% [28], after this ratio, the compressive strength starts to decrease.

It was also revealed that the compressive strength decreased with a shorter distance between the aligned optical fibers, as this led to an excessive propagation of micro cracks [14]. Fig. 3 shows some results regarding the influence of POF content on the compressive strength of LiTraCon.

3.2. Optical fibers alignment

A comparison study of mechanical properties between regularly aligned POF LiTraCon and randomly aligned POF LiTraCon is presented in Table 1 through experimental work achieved by Hen-

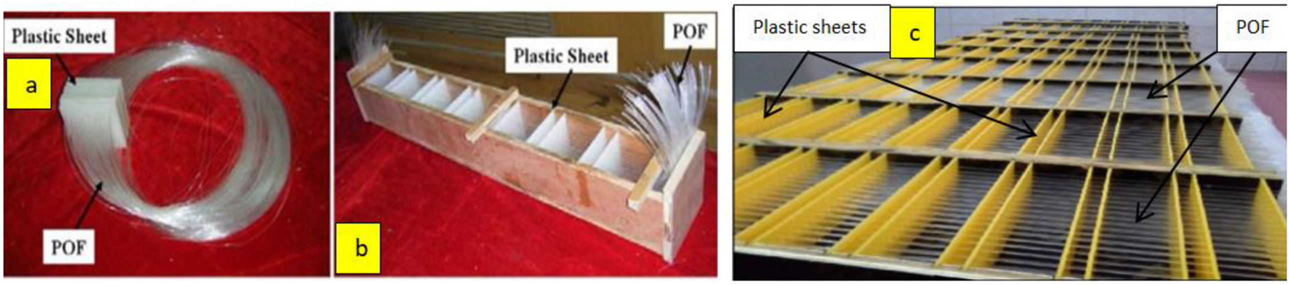

Fig. 2. Preparation of (a) POF (b) LiTraCon cubes (c) LiTraCon prisms [19,23].

Table 1
A comparison study between regularly aligned and randomly aligned POF LiTraCon [16,17].

Increase in POF content% from 0 to:	Decrease in compressive strength of LiTraCon for POF		Decrease in flexural tensile strength of LiTraCon for POF		Increase in capillary water absorption of LiTraCon for POF	
	Regularly aligned %	Randomly aligned %	Regularly aligned %	Randomly aligned %	Regularly aligned %	Randomly aligned %
2	0	11.5	18	20.5	100	209
3.5	5	15	20	32	333	245
5	11	20	18	25.5	413	300

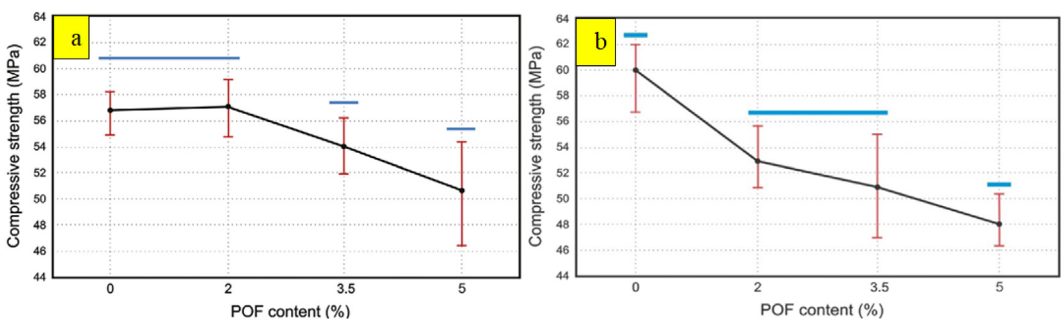

Fig. 3. Influence of POF content on LiTraCon's compressive strength for POF (a) Regularly aligned [16] (b) Randomly aligned [17].

riques et al [16,17]. It is revealed from the results in Table 1 that the effect of regular alignment is better than the random alignment of POF on LiTraCon. Concerning the compressive strength, the highest reduction was 11 and 20% for regularly aligned and randomly aligned POF LiTraCon, respectively, whereas the highest reduction in flexural strength was 20 and 32% for regularly aligned and randomly aligned POF LiTraCon, respectively.

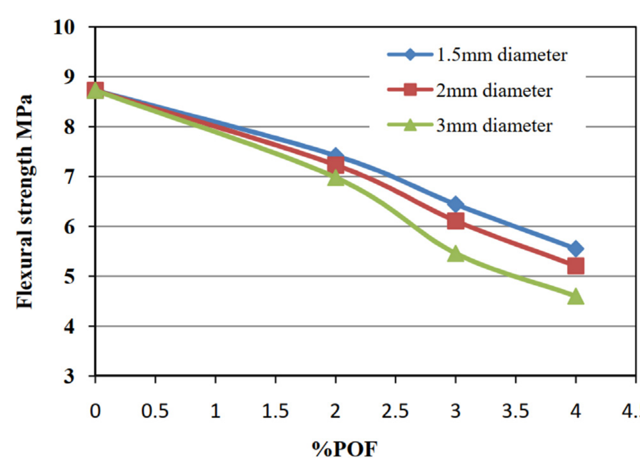

Fig. 4. Flexural strength of LiTraCon decreased as POF content and diameter rose [19].

3.3. Optical fiber diameter

As shown in Fig. 4, Salih et al (2014) [19] found that the flexural strength of LiTraCon decreased as POF content and diameter rose. For POF content less than 2%, the average reduction rate in flexural strength of LiTraCon was about 10.2% for each 1% increase in POF content, whereas For POF content more than 2%, the average reduction rate in flexural strength was about 15.5% for each 1% increase in POF content. Moreover, as the diameter of POF increased from 1.5 to 2 and 3 mm, the lowering in flexural strength of LiTraCon was about an average of 6.5 and 16.5%, respectively.

3.4. Direction of loading

An experimental investigation was carried out by Halbiniak and Sroka (2015) [24] to analyse the effectiveness of the compressive load direction on LiTraCon samples. Results indicated that the existence of POF in LiTraCon reduced the compressive strength of LiTraCon. The reduction amount is relevant to the relation of loading direction with the POF direction in the mould. In addition, it was found that the compressive strength of LiTraCon specimens reduced by about 38% with loading parallel to the POF direction, while it reduced by about 19% for LiTraCon specimens with loading perpendicular to the POF direction, as compared to the compressive strength of specimens excluded from POF.

4. Analysis of scanning electron microscopy (SEM)

Regarding the fiber/matrix zone in LiTraCon, scanning electron microscopy (SEM) analysis has been achieved by some researchers. SEM analysis which is conducted by Henriques et al [16,17] on LitRaCon and illustrated in Fig. 5, demonstrates the impairment of mechanical properties of LiTraCon due to lots of infinitesimal voids and gaps involved in a fragile, pervious and brittle interfacial fiber/matrix zone with a highly smoothened surface of POF which causes weak bonding. In addition, microstructure analysis (SEM) on LiTraCon achieved by Li et al. (2015) [1] as shown in Fig. 6, illustrates numerous numbers of detrimental pores with a diameter ≥ 100 nm accumulated in the fiber/matrix interface which significantly harm the mechanical properties of LiTraCon. Consequently, the pores with a diameter less than 100 nm are neutral and not harmful to the mechanical properties of LiTraCon. Besides, SEM test was achieved by Li et al (2012) [25] and revealed that there are lots of pores existent between optical fibers and cement paste with weakly bonded interfacial area, as shown in Fig. 7. The cracks easily initiate and propagate among the optical fibers within the interfacial zone.

On the other hand, Fig. 8 shows a Microstructure analysis done by Li et al. (2015) [2] and indicated highly compacted material with evenly distributed fibers in the matrix, accompanied with Infinitesimal pores in the fiber/matrix interface. Mixing of highly fine grained binders as a cement replacement (such as silica fume) is a good solution capable of enhancing the mechanical properties of the interfacial fiber/matrix zone [15,16].

5. Durability of LiTraCon

5.1. Imperviousness

The imperviousness has been investigated by He et al. (2011) [23] to evaluate the durability of LiTraCon. Results displayed that the increase in optical fibers content has a detrimental effect on durability due to increasing the perviousness of LiTraCon. The authors recommended two methods to optimize the Imperviousness; the first method is coating the POFs with epoxy resin and the second method is by using POFs having a rough external cover to increase the interference between the POFs and the cement mortar. Besides, using 10% silica fume as partial replacement of cement optimizes the imperviousness of LiTraCon [16,17].

5.2. Water absorption

Water absorption tests on LiTraCon are performed by some authors [16,17,29]. As shown in Table 1 and Fig. 9, a conclusion has been drawn that only the presence of POF has a great negative effect on LiTraCon which is irrelevant to the status of POF alignment in the mold. Thus, by incorporating optical fibers between 2 and 5%, the water absorption capacity raised around 2–5 times the zero fiber content in LiTraCon (Table 1). This is due to lots of pores created in a crisp, permeable and brittle matrix surrounding the optical fibers. Conversely, other water absorption tests on LiTraCon consisting of almost 4% optical fibers showed that the water absorption and sorptivity decreased of about 9 and 0.5% corresponds to plain concrete, respectively, which is insubstantial [29].

6. Transmittance ability of LiTraCon

6.1. Optical fiber alignment

By referring to Table 2 and Fig. 10, the results presented by Henriques et al. [16,17] show that the regularly aligned POFs haven't significantly affected the performance of transmittance ability of LiTraCon as compared to the randomly aligned POF LiTraCon. Thus, the improvement in transmittance ability of LiTraCon is almost the same for both status of POF alignment by increasing POF content from 2 to 3.5% in LiTraCon. Besides, an increase in POF content from 2 to 5% led to an improvement in light transmittance ability of regularly aligned POF LiTraCon of about 22% more than the corresponding improvement for randomly aligned POF LiTraCon.

6.2. Optical fiber content

Table 2 shows numerous results reported by different authors indicating that the transmittance ability is enhanced by increasing the optical fiber content in LiTraCon. Furthermore, it was revealed that 5% is the most cost-effective and the best POF content to present the best quality of aesthetic appearance of LiTraCon with acceptable mechanical properties [5,16], whereas Ahuja and Mosalam (2017) [30] showed that a ratio of 6% of optical fibers imbedded in concrete panels can save 50% of illumination energy and is able to reduce the energy costs by around 18%. However, volumetric fiber content higher than 5% cannot be performed due to the difficulties in filling the voids between the fibers gently without destroying the POF. As a result, the transmittance ability of LiTraCon starts to diminish with fiber content higher than 5% [16]. Besides, it was demonstrated that the light transmission reduced for LiTraCon of gravimetric fiber content exceeds 1.59% due to the short distance between the fibers which is undesirable [14]. Fig. 10 illustrates the effect of optical fibers content on light transmittance ability of LiTraCon.

6.3. Optical fiber diameter

Commonly, the researchers agreed through their experimental works that the larger optical fiber diameter enhances the optical

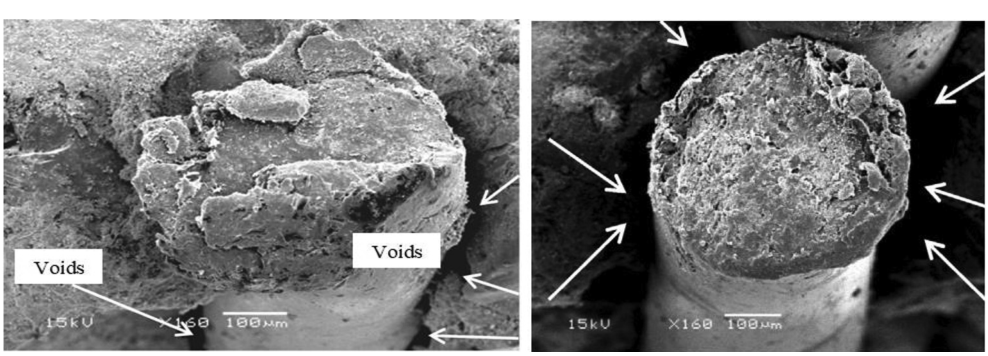

Fig. 5. SEM analysis shows lots of voids in pervious interfacial fiber/matrix zone in LiTraCon [16,17].

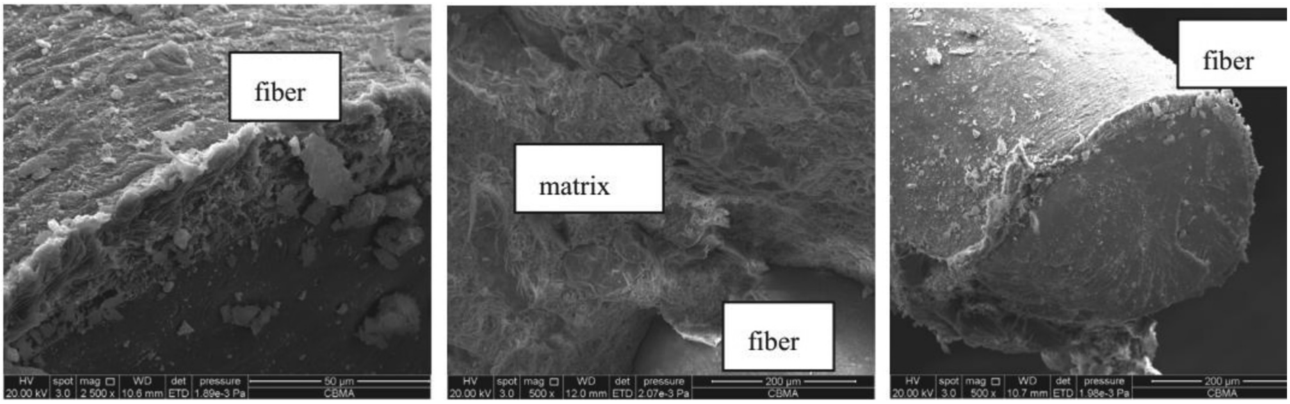

Fig. 6. Microstructure analysis illustrates numerous numbers of detrimental pores with a diameter ≥ 100 nm [1].

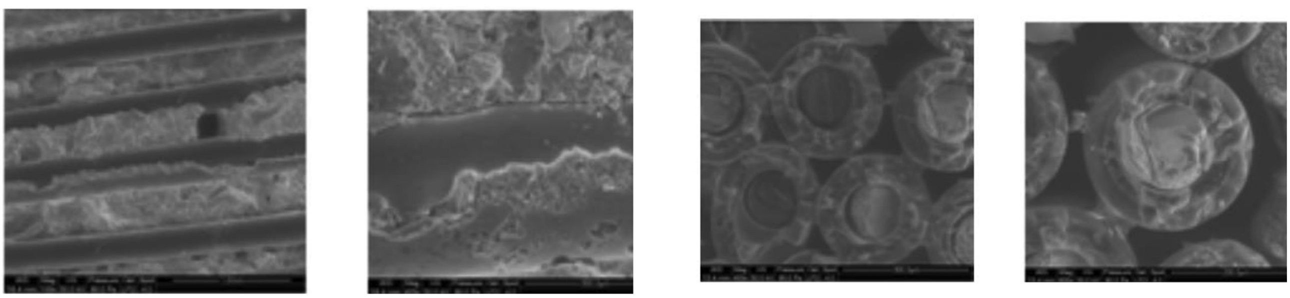

Fig. 7. SEM test reveals lots of pores existent between optical fibers and cement paste [25].

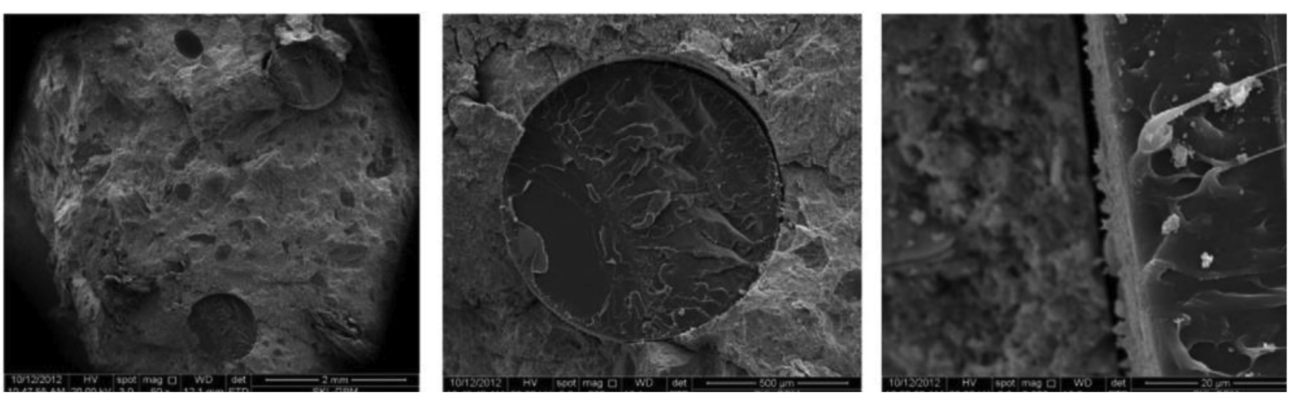

Fig. 8. Microstructure analysis indicated infinitesimal pores in the fiber/matrix interface [2].

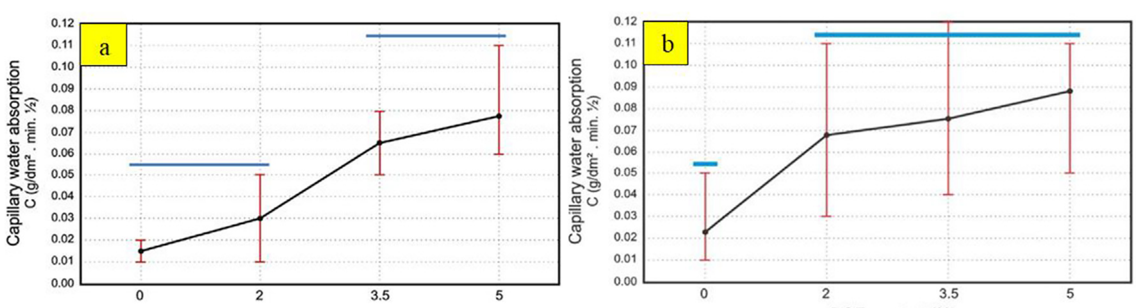

Fig. 9. Effect of optical fibers on water absorption capacity of LiTraCon for POF (a) Regularly aligned [16] (b) Randomly aligned [17].

Table 2
Influence of optical fiber content variation on light transmittance ability of LiTraCon.

Authors	Increase in volumetric/gravimetric* fiber content%		Type of optical fibers	Increase in light transmittance%	Device used in light transmittance measurement
	From	To			
Henriques et al. (2018) [16]	2	3.5	POF	48	Built wooden device
Orderly arranged POF	2	5	POF	226	
Henriques et al. (2020) [17]	2	3.5	POF	52	Built wooden device
Randomly arranged POF	2	5	POF	204	
Li et al. (2015) [1]	1	2	POF	180	Charge-coupled Device (CCD)
	1	3	POF	220	
Li et al. (2015) [2]	1	2	POF	85	optical power meter
	1	3	POF	160	
Altlomate et al. (2016) [14]	0.36*	1.43*	POF	316	electrical circuit setup
	0.36*	1.59*	POF	155	
Singh et al. (2016) [31]	3	4	POF	243	Lux meter
Mahto et al. (2017) [3]	3	5	POF	34	Light Depending Diode (LDR)
He. et al. (2011) [23]	1	2	POF	66	Newport 835 Optical Power Meter
		3		233	
		5		516	
		6		666	
Mohan et al. (2018) [12]	1	2	POF	87	Lux meter testing setup
	1	3		175	
	1	4		205	
	0.5	1.8	Epoxy resin rods	175	
	4 (POF)	0.5(epoxy rods)	-	160	
	4 (POF)	1.8 (epoxy rods)		620	
Pradheepa & Krishnamoorthi (2015) [21]	2	4	POF	8-21	digital Lux meter
Yue et al. (2012) [25]	10	20	GOF	40-50	UV765 UV-visible spectrophotometer

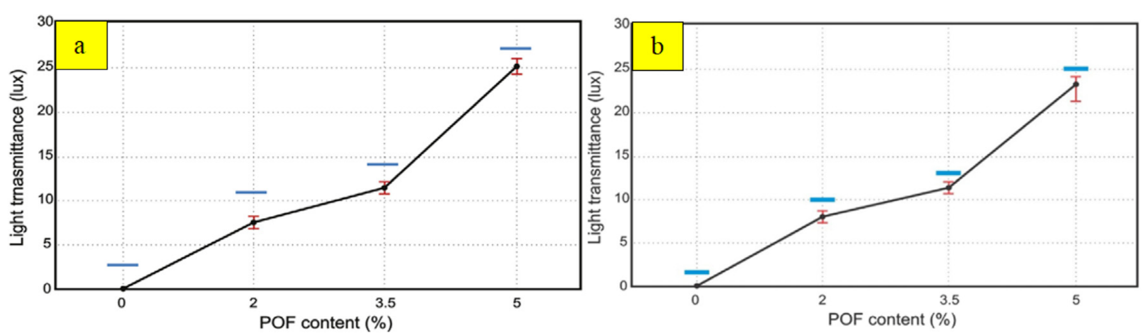

Fig. 10. Effect of optical fibers content on light transmittance ability of LiTraCon for POF (a) Regularly aligned [16] (b) Randomly aligned [17].

power ability of LiTraCon [1,2,14,21,25]. This is analogous to the effect of a larger cross section of tube which leads to a greater fluid discharge. Similarly, the larger diameter of optical fiber means larger cross section area which transmits greater light quantity. Finally, utilizing 2 mm diameter of POF is the best diameter to produce LiTraCon with higher compressive and flexural strength [19]. Table 3 shows some authors results of the impact of optical fiber diameter increase.

6.4. Distance from light source

Test results gathered by Li et al. (2015) [2] state that the light transmittance capacity of LiTraCon diminishes as the distance between the light source and specimen increases. For four-optical fiber specimen, the light transmittance capacity diminishes by about 84, 95 and 98% as the distance between light source and specimen increases from 0 to 5, 10 and 20 cm, respectively.

Table 3
Influence of optical fiber diameter variation on light transmittance ability of LiTraCon.

Authors	Increase in optical fiber diameter mm		Type of optical fibers	Fiber content% By volume By weight*	Increase in optical power ability%
	From	To			
Li et al. (2015) [1]	0.5	1	POF	5	75
Li et al. (2015) [2]	0.5	1	POF	3	90
	0.5	1		4	110
Altlomate et al. (2016) [14]	0.5	0.75	POF	0.36*	190
	0.75	1.5		1.43*	300
Pradheepa & Krishnamoorthi (2015) [20]	0.25	0.75	POF	2	17-30
	0.25	0.75		4	25-31
Yue et al. (2012) [24]	0.05	0.0625	GOF	10	50
			GOF	20	120

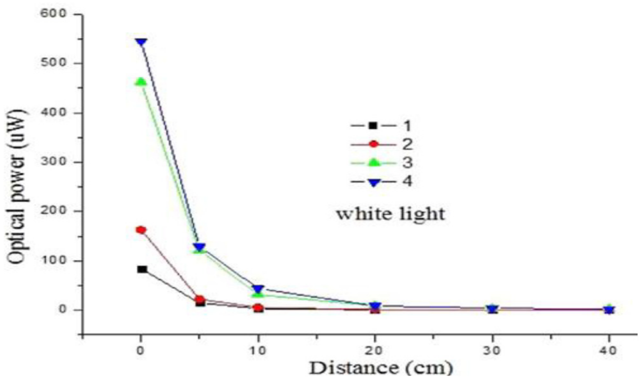

Fig. 11. Influence of light source distance on optical power of LiTraCon [2].

However, when the distance increased to more than 20 cm, the optical power for specimens with different fiber content almost exhibits the same ability. Fig. 11 shows the optical power variation of LiTraCon with the distance from the light source.

7. Conclusion

Regarding the aforementioned study, a number of concluding comments are derived as follows:

- To obtain better homogeneity and compaction, with better light transmittance of LiTraCon, it is convenient to exclude the coarse aggregate from the ingredients fabricating a mix of "light transmitting cement mortar"
- Due to the vibrating of concrete, there are concerns of missing the optical fibers alignment. To get rid of this problem, self-compacting concrete is the best solution for LiTraCon fabrication with good homogeneity.
- Using highly fine grained binders as a cement replacement in LiTraCon serves in enhancing the strength, cohesion and to reduce the cracks propagation in the fiber/matrix interface.
- The mechanical properties of LiTraCon deteriorated with increasing the POF content. In addition, the effect of regular alignment is better than random alignment of POF on the mechanical properties of LiTraCon. Moreover, the compressive strength reduction amount in LiTraCon is relevant to the relation between the loading direction and POF direction inside samples.
- LiTraCon suffers from higher rate of water absorption as POF increases due to lots of pores created in a crisp, permeable and brittle matrix surrounding the optical fibers. In addition, water absorption in LiTraCon is irrelevant to the status of POF alignment in the mold.
- The light transmittance ability of LiTraCon is enhanced by increasing the optical fiber content. However, the alignment status of POF hasn't substantially affected the performance of light transmittance ability of LiTraCon. In addition, transmittance ability for LiTraCon has diminished with fiber content higher than 5–6% due to the difficulties of filling the voids between the fibers gently.
- Larger optical fiber diameter improves the optical power ability of LiTraCon. In addition, 2 mm diameter of POF is the best diameter to produce LiTraCon with better mechanical properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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