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Experimental study of light transmitting cement-based material (LTCM)

Yue Li [a], Jiaqi Li [a,b,*], Yuhong Wan [c], Zhiyuan Xu [a]

[a] The Key Laboratory of Urban Security and Disaster Engineering, MOE, Beijing Key Lab of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, 100124, PR China

[b] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, USA

[c] College of Applied Sciences, Beijing University of Technology, Beijing 100124, PR China

HIGHLIGHTS

- A light transmitting material prepared by optical fiber fabric and mortar.
- Effects of volume fraction of fiber on the strengths of material are studied.
- Factors affecting the transmittance of light transmitting material are studied.
- The microstructures of light transmitting cement-based material are analyzed.

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ABSTRACT

Light transmitting cement-based material (LTCM) was prepared by polymethylmethacrylate (PMMA) fibers, Portland cement, aggregates, deforming agent and water reducers in a given proportion. The compressive and flexural strengths of LTCM prepared with different diameters and volume fractions of optical fibers were measured at the age of 28 d. The compressive and flexural strengths of LTCM specimens decreased with an increasing volume fraction of fiber. Factors such as distance from the light source to specimen, diameter and volume fraction of fiber, and the variety of light sources that affect the optical power of LTCM were studied in this paper. The experimental results demonstrate that the optical power was significantly affected by the distance from light source and specimen, and the diameter and number of fibers. The matrix material, cross section of optical fiber, and the interface between fiber and matrix were analyzed by SEM.

1. Introduction

Traditional light transmitting materials are primarily made of glass and organic composite materials. The light transmitting properties of these kinds of materials entirely depend on matrix materials. Compared with glass and organic composite materials, the light transmitting cement-based material (LTCM) is a new type of light transmitting material. Its primary composition is cement-based material—optical fiber composite material, the matrix of which is high consistency cement mortar or concrete. A number of optical fibers are embedded into the matrix material with a specific spatial arrangement pattern. Unlike the transmitting mechanism of organic composite materials, which is determined by matrix materials, LTCM relies on vast optical fibers which transmit lights between the two sides of the blocks [1,2], as shown in Fig. 1.

Light transmitting cement-based material has the following characteristics [2,3]: (1) Excellent light transmitting properties: The light transmittance of polymethylmethacrylate (PMMA) fibers is able to reach up to 90%. LTCM can obtain high transmittance by means of altering the number of fibers and spatial arrangement pattern of fibers. (2) Good mechanical properties: Since the volume fraction of optical fibers is relatively small, the mechanical properties of LTCM include only few negative effects, and strengths decrease slightly within the range of fiber volume. Therefore, LTCM has been applied as construction material and bearing structure. (3) Lightweight: Compared with normal cement mortar and concrete, the density of LTCM decreases with increasing volume fraction of optical fibers. (4) Versatile decorative effects: By means of adjusting the amount of fibers, spatial arrangement pattern of

* Corresponding author at: School of Civil Engineering, Beijing University of Technology, 100124, PR China and Department of Civil and Environmental Engineering, University of California, Berkeley, USA.

E-mail address: Jiaqi.li@berkeley.edu (J. Li).

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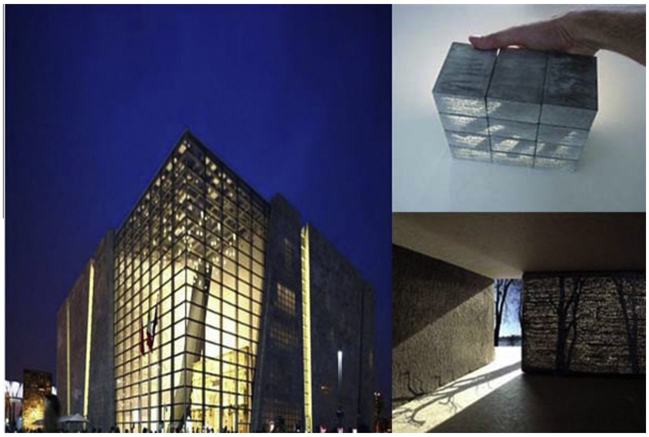


Fig. 1. Light transmitting cement-based materials.

fibers, and composition of cement matrix, LTCM can form various textures and colors, and fancy artistic effects are able to achieve under lights.

Hitherto, few studies regarding LTCM have been reported, and previous studies were mainly business news and product presentations [4,5]. This indicates that LTCM is a new material, and studies on LTCM still remain in its primary stage.

Hungarian architect Aron Losonczi, etc. invented LTCM [1], and named it as LiTracon (abbreviation of light transmitting concrete) in 2002. The product was blocks of polished prefabricated fiber concrete, and its composition was 96% concrete and 4% fiber. The maximum dimension of blocks was 600 mm × 300 mm, and the colors of them were grey, black or white. The compressive and flexural strength were 50 N/mm^2 and 7 N/mm^2, respectively. These products have been used in Hungary, America, France, Belgium, Germany and Japan. Vitreous optical fibers with diameters of 2–200 μm was used in LiTracon. The optical fibers can be distributed randomly and designed to specific geometric figures [3].

Andreas Roye's study utilized two types of optical fibers [3]: vitreous fibers with a diameter of 70 μm, and polymeric fibers with diameters of 1 mm and 3 mm. The fibers were preprocessed before preparation, to make the fibers bended adequately. Textile process, such as knitting and warp/weft yarn, was utilized to form a layered fabric. Aggregate of self-compacting concrete was gravel with maximum size of 6 mm. The fibers were fixed in concrete evenly. Fiber-concrete was an ideal layered composite, and between the fabrics were the layers of concrete. The volume fraction of fiber was 3–6%. The blocks were cut and polished after demoulding, and light transmitting concrete with different sizes could be obtained.

The authors [6,7] used cement mortar and cement paste as matrix materials, and prepared the LTCM. Without textile manufacturing process, optical fibers were embedded into the matrix materials by means of parallel arrangement patterns. The compressive strengths and light transmitting properties were tested, and their microstructures were analyzed by SEM method. Chinese patent *Preparation method of light transmitting cement-based material using optical fibers in parallel distribution* (*ZL201110021994.1*) [8] was reported as a preparation method for producing LTCM, which had good light transmitting properties and versatile decorative effects. However, it exposed a few drawbacks: high cost, sensitive to alkali attack and shrinkage cracking, and complicated preparation. Chinese patent *Preparation method of light transmitting concrete using optical fiber fabrics* (*ZL201110022019.2*) [9] innovated in composition, preparation technology, and solved the problems above.

Thus, as a new construction material, studies on LTCM are still very rare, especially material composition, design methods, characterization of light transmitting properties, and microstructure of LTCM. In this work, organic optical fibers were used for preparation of LTCM, composition, preparation, design method, physical and mechanical properties, light transmitting properties, and microstructures were discussed.

2. Material and methods

2.1. Raw materials

The cement used in this study was type I/II Portland cement based on China national standard GB175-2007, its 3 d and 28 d compressive strengths were 21.4 MPa and 48.6 MPa, respectively, and its apparent density was 3100 kg/m^3. The apparent density of blast furnace slag with specific surface of 540 m^2/kg was 2880 kg/m^3. The sand used in this study was China ISO standard sand based on China national standard GB/T17671-1999 and ISO 679:1989. The particle size distribution of sands was continuous grading of 0.06–1.18 mm. The properties of the cementitious materials are given in Table 1.

The optical fibers used in this study were PMMA fiber with a diameter of 1.0 mm and 0.5 mm, respectively. The coating material of the fiber was fluororesin. The transmittance loss rate of fiber at 650 nm wavelength was less than 350 dB/km. The numerical aperture of fiber was 0.5, and its effective bending diameter was eight times greater than the diameter of optical fiber. The range of operating temperature was −20∼70 °C. The water reducer was polycarboxylate superplasticizer with water reducing rate of 35%. The antifoaming agent was viscous organosilicone emulsion, its pH value was 8, and its solid content was 30%.

2.2. Preparation and testing methods

2.2.1. Cement mortar

The matrix material of LTCM was a high consistency cement mortar. The mix design of cement mortar was shown as follows: the mass ratio of sand to cementitious materials was 0.75; the mass ratio of cement to blast furnace slag was 4; the addition of water reducer was 0.2% by mass of cementitious materials; and the addition of antifoaming agent was 0.2% of the total mass.

2.2.2. Preparation and fixation method of fiber fabric

Preparation method of the fiber fabric: The optical fibers are woven into a monolayer fabric. Optical fibers are distributed in a single direction, and cotton yarns are used to connect the optical fibers. The intervals of optical fibers stabilize in a range between 3 and 6 mm. The preparation of optical fiber fabric is shown in Fig. 2.

There are two types of fixation methods of optical fiber fabric with the mold. The features of these methods are described as follows:

Method A: The parallel steel bars, which are in the direction of the long axis of uncovered end, are fixed into the mold at a specific designed distance. The optical fiber fabric is twined in bars, the bars are attached on both the bottom and the top of the mold, and the optical fiber fabric is straightened by the bars. The schematic diagram of the mold and actual forming process are shown in Fig. 3.

Method B: Steel bars, which are in accordance with desired figures, are embedded into the base of uncovered wooden mold. The twining optical fiber fabric can be formed in designed shapes. Its schematic diagram of the mold and specific forming process are shown in Fig. 4.

Table 1
Chemical composition (by mass) and physical properties of raw materials.

Materials	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	R_2O (%)	Cl (%)	Density (kg/m^3)	Blaine surface (m^2/kg)
Cement	62.6	21.3	4.67	3.31	3.05	2.11	0.75	0.007	3100	381
Slag	34.54	28.15	16	1.1	6	0.32	0.91	0.005	2880	540

Note: R_2O: $K_2O + Na_2O$.

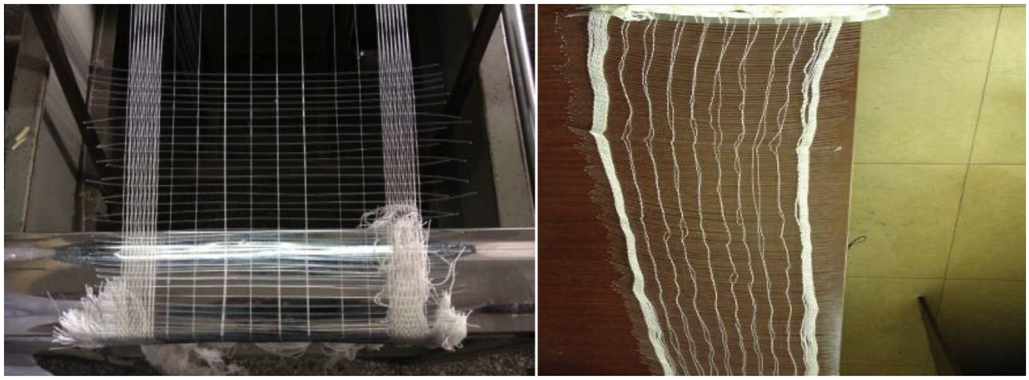


Fig. 2. Preparation of the optical fiber fabric.

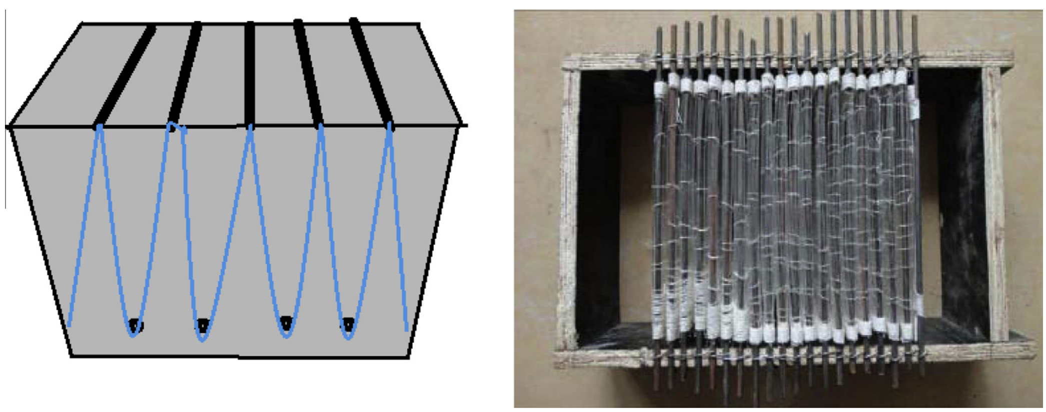


Fig. 3. The schematic diagram and images of A mold.

Fig. 4. The planform and images of B mold.

2.2.3. Forming process of LTCM

After the optical fiber fabric was fixed in the mold, the molds were filled with fresh cement mortar. The examples were cured for 28 days. Afterwards, the hardened cement mortar blocks were cut into slices with different thicknesses. The LTCM formed after the cutting sections, as shown in Fig. 5, were polished and sprayed with silicone oil.

2.2.4. Testing methods of light transmitting

The light transmitting properties of LTCM were measured by optical power meter, which is used to measure the optical power of optical energy through optical fibers or absolute optical power of light, and to evaluate the transmission quality of optical fibers. The apparatus includes a stable light source, a detector and a display. The diameter of detection surface of the detector is 1 cm. In this study, the optical power meter was used to measure the optical power of LTCM at various distances between LTCM and the light source. Simulated and actual testing optical paths were shown in Figs. 6 and 7, respectively. The light sources were white light and monochrome red light (wavelength = 633 nm).

2.2.5. Strength tests and microstructure analysis

The samples were cut into prisms with the dimensions of $4 \times 4 \times 16$ cm. Compressive and flexural strength tests of hardened pure cement mortar and LTCM were carried out in accordance with China national standard GB175-2007

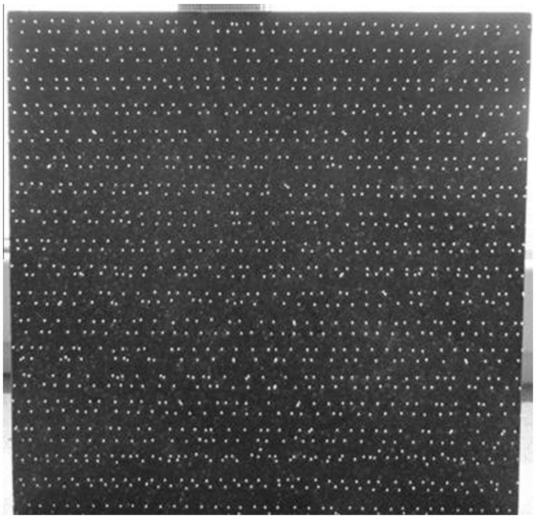


Fig. 5. Completed LTCM sample.

(title: Common Portland Cement). For the flexural strength test, as shown in Fig. 8, the distribution of optical fibers is perpendicular to the direction of the force. Compressive strengths were tested after flexural strength tests. The compression areas were 4 × 4 cm, and the compressive and bending stress are in the same direction. The fluidity (consistency) test of high consistency cement mortar was carried out in accordance with China national standard GB/T2419-2005 (title: Test method for fluidity of cement mortar).

The SEM images of LTCM were collected by QUANTA-FEC250 SEM device. LTCM was cut with a sharp knife into 3.0–5.0 mm pieces which contained a few fibers. At the curing age of 28 days, the samples were analyzed by SEM.

3. Results and discussion

3.1. Strength results

The composition and mechanical properties of pure cement mortar and LTCM are given in Table 2. Table 2 shows that the strengths of LTCM are slightly less than that of pure cement mortar. The strengths of specimens decrease with the increasing volume fraction of optical fibers. For the specimen whose volume fraction reaches up to 4%, the compressive strength is 81% of that of pure cement mortar, and the flexural strength is 83% of that of pure cement mortar. The consistency of pure cement mortar was 125 mm, which indicates that the mortar exhibits has good consistency. Meanwhile, the mortar exhibited no bleeding or segregation phenomena. It is found that the surfaces of sections of mortar specimens and LTCM had no visible pores after flexural strength tests, and the surfaces were compact.

3.2. Transmitting results and analysis

3.2.1. Transmitting analysis of specimens in different distances

The light transmittance of LTCM in Table 2 was measured by an optical power meter. It should be noticed that the detector of 1 cm-diameter-range measured the transmitted light from 1 to 4 optical fibers of the specimens. The results were given in Figs. 9 and 10, respectively. The LTCM samples using optical fibers with diameters of 1 mm and 0.5 mm were labeled as Sample A and B, respectively.

From Figs. 9 through 10, for both Sample A and B, when the number of fibers is a certain value, regardless of white or red light, the optical power decreases with an increasing distance from the light source to the specimen. Moreover, initially the optical power decreases significantly, then the decline rate of optical power decreases gradually, and finally almost tends to be the same. For specimens at the same distance, the optical power increases gradually with the increase of fiber number in specimen. However, for specimens with different numbers of fibers, regardless of white or red light, when the distance rises to a specific range, the optical power basically tends to be the same. This is because the emergent light of each fiber is scattered, the spot gets larger with increasing distance, and the light wave which incident on the small detection surface decreases gradually.

3.2.2. Optical power comparative analysis of Sample A and B

In the case of the same number of fiber and distance, this study introduces a ratio of optical power of Sample A to B to analyze the effects of fiber diameter on light transmitting. The ratios of optical power are obtained, as shown in Fig. 11.

Fig. 11 illustrates that, for specimens using fibers with diameters of 1 mm and 0.5 mm, in the case of the same thickness of the specimens (the same length of optical fibers), the ratio of optical power is not always close to four (the ratio of fiber section area). The variations of the ratio are listed as follows:

(1) When there is only one fiber in the test zone, and the distance from white light source to specimen is 0, the ratio is 4.72 (greater than the ratio of fiber section area). Afterwards, as the distance increases, the ratio decreases to a range of 2.5–3.5. However, when the distance from red light source to specimen is 0, the ratio is 3.67 (smaller than the ratio of fiber section area). Then, with the increase of distance, the ratio decreases to a range of 1.5–2.5.

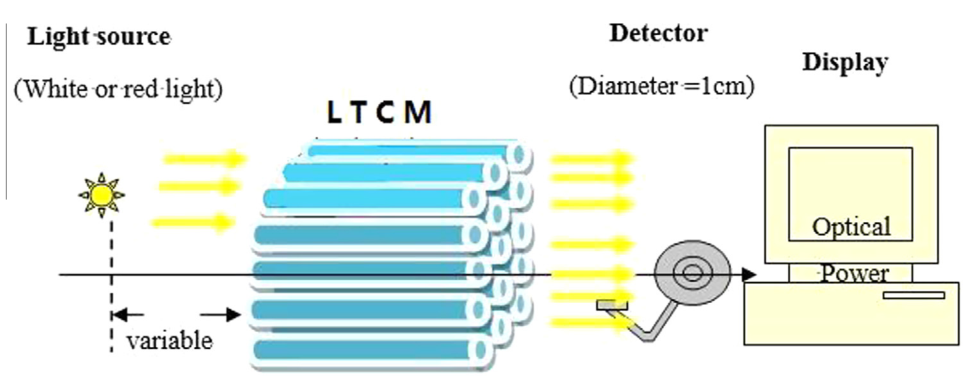


Fig. 6. Simulated testing optical path.

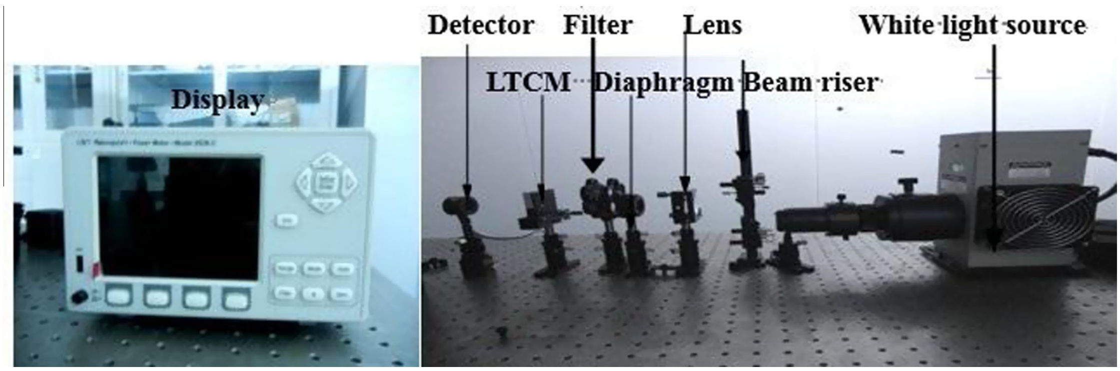


Fig. 7. Actual testing optical path.

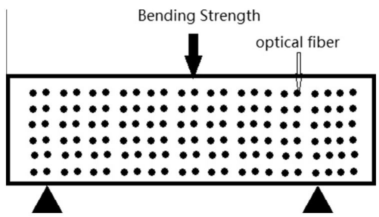


Fig. 8. The schematic diagram of flexural test of LTCM.

Table 2
Compressive and flexural strength results.

Diameter of optical fiber (mm)	Volume fraction (%)	The number of fibers in detection surface	Strength at 28d (MPa)	
			Compressive strength	Flexural strength
–	–	–	70.5	9.1
1	1	1	67.3	8.7
1	2	2	64.1	8.2
1	3	3	61.5	8.0
1	4	4	57.6	7.6
0.5	0.25	1	70.1	9.1
0.5	0.5	2	69.1	8.8
0.5	0.75	3	68.2	8.8
0.5	1	4	66.7	8.6

(2) When there are two fibers in the test zone, and the distance from white light source to specimen is 0, the ratio is 4.5 (greater than the ratio of fiber section area). Then, although the ratio decreases gradually with the increasing distance, it stays between 3.5 and 4.5. When the distance from red light source to specimen is 0, the ratio is 4.1 (slightly greater than the ratio of fiber section area). Then, the ratio decreases to a range between 1.8 and 3.6 with the increase of the distance.
(3) When there are three or four fibers in the test zone, and the distance from the light source to specimen is 0, regardless of white or red light, the ratio is approximately two. Then, the ratio decreases with the increase of the distance, but it is still greater than one.

The causes of the above phenomena are as follows: light interference and scattering happen due to complex light propagation process. The fact that the light transmitting ability of fiber is not simply the superposition of translucent area, makes the optical power ratios of Sample A to B are not always four, but a particular range of value. In addition, scattering of emergent light waves happens due to uneven and irregular sections of optical fibers at the exit end, which leads to the distribution of incident light wave field in the detection area is irregular. In addition, small variation in relative position of optical fibers also affects the wavelengths of lights received by the detector. As the relative position of the two fibers is far, the detector is not able to receive lots of scattering lights simultaneously. Similarly, as the relative position is adjacent, more scattering lights can be received by the detector simultaneously.

3.3. Microstructure analysis

The microstructure of Sample A was studied by SEM at the age of 28 days. The results are shown in Fig. 12. As shown in Fig. 12(a),

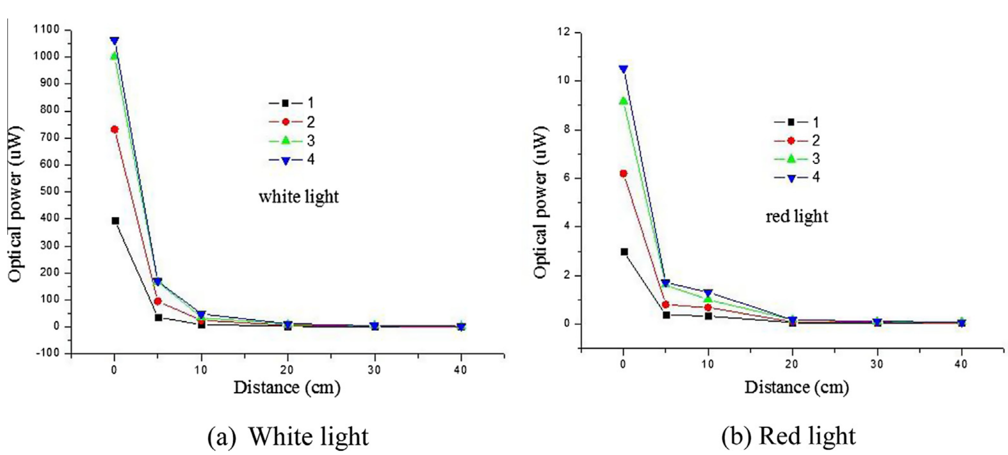
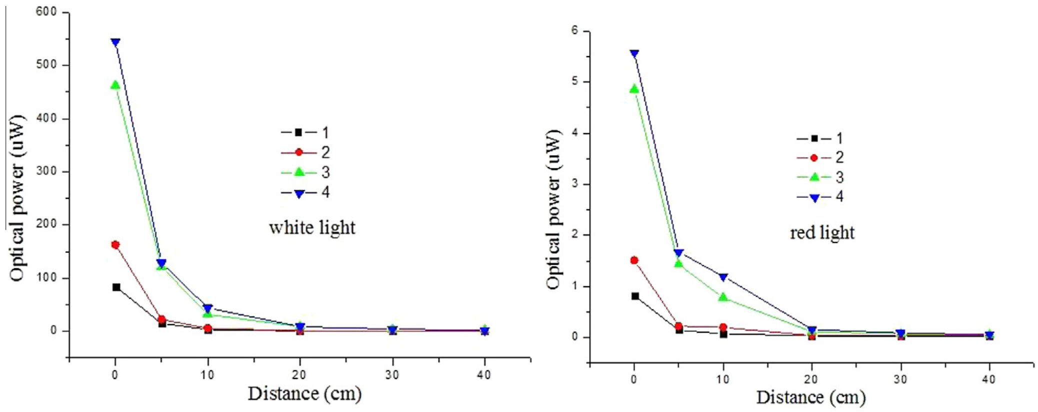
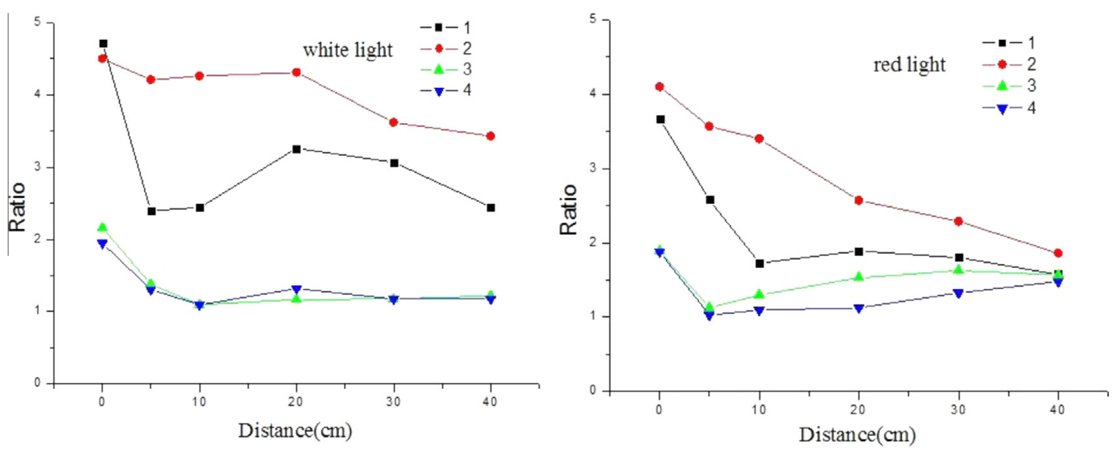


Fig. 9. The optical power contrast between various number of fibers under white and red light (Sample A).



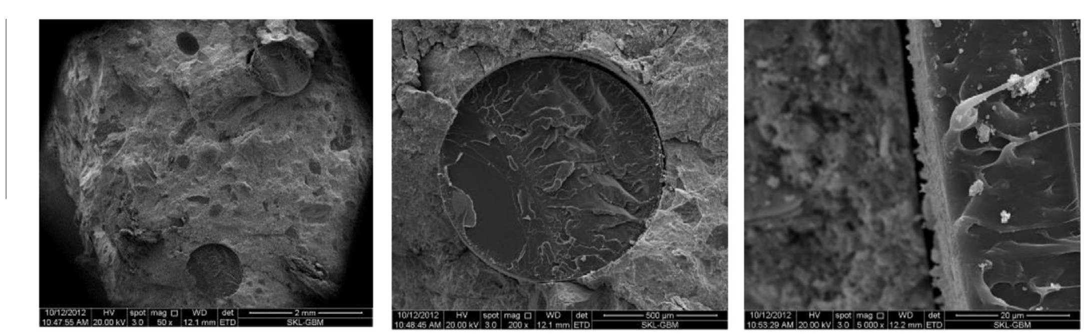
(a) White light (b) Red light

Fig. 10. The optical power contrast between various number of fibers under white and red light (Sample B).



(a) White light (b) Red light

Fig. 11. Optical power ratio of Samples A and B.



(a) Matrix with optical fibers (b) cross section of optical fiber (c) fiber/matrix interface

Fig. 12. SEM images of LTCM.

the matrix of LTCM is compact, and the optical fibers are embedded in matrix evenly. This indicates that, the components and mix proportion of cement mortar matrix is effective, the proposed arrangement methods of optical fibers make the fibers evenly distributed in mortar matrix. It can be seen that the cross section of PMMA fiber is circular. The inner part of fiber is the core material of fiber, and the outer part is an ultra-thin coating which protects the core. This reveals that, the morphology of optical fiber is introduced, which is helpful to understand the microstructure of optical fiber, and it is not visible to naked eyes on gross. The fracture section of fiber is roughness although it looks very smooth by naked eyes, which means the surfaces of the intact fibers actually are still rough. Surface roughness induced scattering loss is one of the important properties of an optical waveguide. (Fig. 12(b)). This explains why the microstructure of cross-section of optical fiber affects the light transmitting properties of LTCM, and we re-explain it as: The fracture section of fiber is roughness although it looks very smooth by naked eyes, which means the surfaces of the intact fibers actually are still rough. Scattering of emergent light waves happens due to uneven and irregular sections of optical fibers at the exit end, which leads to the distribution of incident light wave field in the detection area is irregular. Even the interface between fibers and cement matrix binds well in small magnification observation, tiny gaps still exist at large magnification observation (Fig. 12(c)).

4. Conclusions

LTCM, which can be used in wide application areas, has excellent light transmitting properties, good mechanical properties and versatile decorative effects. Based on the research presented, the following conclusions can be drawn:

1. High strength and high flowing cement mortar were prepared as matrix material. The preparation of optical fiber fabric, the two fixation methods for fabric fixing in the mold, and the preparation process of LTCM were proposed. LTCM was obtained by the above processes.
2. The strengths of LTCM were slightly smaller than that of cement mortar without optical fibers. As the volume fraction of optical fibers increased, the strengths of specimens decreased gradually. For the specimen whose volume fraction reached up to 4%, the compressive strength was 81% of that of pure cement mortar, and the flexural strength was 83% of that of pure cement mortar.
3. The light transmitting properties of LTCM were measured by an optical power meter. In terms of specimens embedded fibers with varying diameters, when the number of fiber was a certain value, regardless of white or red light, optical power decreased with an increasing distance from the light source and the specimen. In case of the same distance, the optical power of specimens increased gradually with the increasing number of optical fibers. However, for specimen mixing different numbers of fibers, regardless of white or red light, when the distance increased to a specific range, the optical power tended to be the same.
4. For the same number of fibers, the optical power ratio of specimens using fibers with a diameter of 1 mm and 0.5 mm was not always close to four (the ratio of fiber section area). When there were one or two fibers in the test zone, and the distance from the light source and specimens was 0, the ratios were in a range of 3.67–4.72. Afterwards, the ratio decreased with the distance increased. When there were three or four fibers in the test zone, and the distance was 0, the ratios were approximately two. Then, the ratio decreased with the increase of the distance, but it was still greater than one.
5. Based on SEM method, microscopic morphological characteristics of LTCM were analyzed. It was found that the matrix was compact and the fibers were embedded in matrix evenly. The fracture section of PMMA fiber was circular and rough. Tiny gaps existed on the interfaces between optical fibers and cement matrix.

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