Research Article

Preparation and Study of Resin Translucent Concrete Products

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The development of new building materials is a crucial engine for promoting the development of green energy efficient buildings. In this paper, based on the excellent properties of light guiding of resin materials, a new type of resin translucent mortar-based concrete (RTMC) was researched; meanwhile, transmittance properties, mechanical properties, and thermal performance were studied, respectively. The results showed that the resin material possessed excellent light transmittance within the thickness of 100 mm, which can be as high as 93%. Moreover, when the area ratio was within 5%, the compressive strength of RTMC was close to that of plain concrete. Besides, RTMC had excellent thermal performance that the thermal conductivity of RTCM was 0.3815 w/(m·K), which was 60% lower than 0.89 w/(m·K) of plain concrete.

1. Introduction

Against the background of the intensified energy crisis, energy conservation has obtained the worldwide attention for decades [1]. In the meantime, ever since it had emerged for the first time, concrete impressed people with its rough, heavy, and cold image [2], which set up a huge barrier to the architect's design and creation. Given this, it is of great significance to develop a new kind of building material which can organically integrate green energy saving with aesthetics. In 2001, the concept of transparent concrete was first put forward by the Hungarian architect Aron Losonzi [3]. The first transparent concrete block, named as LiTraCon, was successfully produced in 2003 [4]. Since this kind of concrete is the mixture of the optical fiber or plastic resin and ordinary concrete, light can pass through it. However, the cost of an optical fiber as the light guide is extremely high, and the layout technology of the optical fiber is complicated, which hinders the large-scale production and popularization of transparent concrete. In view of this, in 2010, the Italian Cement Group developed a new type of light-transmitting concrete (Figure 1) by using transparent resin which was to embed preformed resin in fine-grained concrete to achieve light transmission [5]. Subsequently, the Italian cement group produced its products, applied them to the Italian pavilion at the Shanghai

World Expo and received extensive attention from scholars [6]. BYD Company Limited [7–9] disclosed a production process of transparent resin concrete in 2015, in which semihardened concrete was first drilled and resin was potted into holes. In 2014, Xingang and Xuna [10] proposed a way of premolding resin guide light first and embedding them into concrete as shown in Figure 2.

Although researches on the transparent concrete have obtained some achievements over the past decades, transparent concrete cannot be regarded as a mature building material. The method mentioned above can achieve the production of transparent resin concrete [11–13]. However, the primary focus of the transparent concrete technology previously has been on its aesthetic appeal and its application in artistic design [14–16]. Thus, as a new construction material, studies on the transparent concrete are still very rare, especially the mechanical, transmittance, and thermal properties [17–21]. In order to improve the above insufficiency, this paper designed a new type of resin translucent mortar-based concrete (RTMC) by using the unsaturated polyester resin as the light guide material. The silica gel is used as the mold for molding the resin light guide body and providing a device for producing this type of silicone mold. The process was simple in operation, low in cost, and high in production efficiency. Furthermore, it

FIGURE 1: Translucent concrete of Italian pavilion.

FIGURE 2: Resin transparent concrete.

overcomes the shortages of the existing light-transmitting concrete production process in terms of production efficiency, cost, and product quality. Besides, the light transmission characteristic, mechanical properties, and thermal performance of RTMC were researched, respectively [22].

2. Materials and Methods

2.1. Raw Materials. In order to prepare the slurry with good workability, PO42.5R ordinary Portland cement (Dalian Xiaoyetian Cement Co., Ltd.), river sand with a fineness modulus of 2.9, grade I fly ash, and the polycarboxylic acid superplasticizer (powder) were used as raw materials. After several trials, the optimum mix ratio of self-compacting cement mortar was determined, as shown in Table 1.

As a kind of energy-saving building material, light-transmitting concrete needs to use light transmittance as the key evaluation index for the selection of the light guide body [23]. Glass is the only light-transmitting material adopted in large-scale applications in buildings. Its light transmission rate can reach more than 80%; plastic optical fiber (POF) can transmit light as high as 93%, and unsaturated polyester resin can reach as high as 94%. The above three materials meet the requirement in light transmittance, but their performance in density, mechanical properties, and thermal performance are different.

As shown in Table 2, the density of glass is much higher than organic glass and unsaturated polyester resin. It meant that the glass is featured with the highest weight that is inconsistent with the requirement of high strength and light weight of green building materials. Glass is fragile when

TABLE 1: Mix ratio of self-compacting cement mortar.

Item	Cement	Sand	Water	Fly ash	Water reducer
Quality (g)	302	523	114	85	2.5

subjected to impact, has many safety hazards, and its heat-insulating performance is relatively low. Meanwhile, glass and POF should be processed under high temperature conditions. However, unsaturated polyester resin can be molded at room temperature and had obvious advantages in terms of high transmittance and thermal performance [24]. Moreover, the price of resin is nearly five times lower than that of optical fiber, and the corresponding price of RTMC is much lower. Therefore, in this paper, unsaturated polyester resin was chosen as the light guide material.

2.2. Preparation of Resin Translucent Concrete Products.

Usually, the key process of making transparent concrete was that POFs were through the holes of two plastic sheets which were fixed on the slots of steel form work shown as Figure 3 [25]. The fabrication was complex and time-consuming. Thus, this paper made a resin light guide body (Figure 4) that could be molded one time and the production time can be saved. The prefabrication of the body was the core of RTMC fabrication and its quality directly determined the light-transmitting performance of RTMC [26]. The process of resin light-transmitting concrete production included four steps of the manufacture of the light guide body model, the manufacture of the silicone mold, the manufacture of the light guide body, and the embedding of cement matrix.

2.2.1. Manufacture of the Light Guide Body Prototype.

The RTMC prepared in this experiment was the standard cube of $100 \times 100 \times 100$ mm. For example, the body had a total of 16 light guide branches and the cross section diameter was 16 mm. Meanwhile, in order to connect each light guide branch as a whole, the connecting part with the length of 90 mm and the thickness of 9 mm was set in the middle. The original shape of the light guide body was made of plastic and wood in a 1 : 1 ratio (Figure 5).

2.2.2. Manufacture of the Silicone Mold.

The silicone and the curing agent were weighed according to the ratio of 100 : 2, next, mixed rapidly and thoroughly for half a minute, and then slowly poured into the mold (Figure 6). Reduced by half the silicone mold to completely cure within four hours and it was used as a pedestal and flipped back into the mold, and No. 8 wax was evenly coated on the contact surface of the mold to facilitate mold splitting. Next, the certain amount of silicone and curing agents was prepared in the same proportion and poured into the mold. The silicone liquid surface just reached the upper end of the light guide model (Figure 7(a)). Finally, the whole was divided into two parts of the upper and lower mold (Figure 7(b)) after curing for four hours.

2.2.3. Manufacture of the Light Guide Body. First, the resin and the accelerator were mixed in the ratio of 100 : 0.8 and

TABLE 2: Comprehensive performance comparison of various types of light-transmitting materials.

Material category	Transmittance parameter test	Density (g/cm^3)	Mechanical properties	Process performance	Thermal conductivity ($\text{W}/\text{m}\cdot\text{k}$)	Price/ dm^3
Glass	80%	2.50	Fragile	Thermal forming	1.10	5\$/ dm^3
POF	93%	1.18	Unbreakable	Thermal forming	0.19	32\$/ dm^3
Unsaturated polyester resin	94%	1.55	Unbreakable	Normal temperature molding	0.16	6\$/ dm^3

FIGURE 3: Fabrication of POF transparent concrete.

FIGURE 4: Resin light guide body.

FIGURE 5: Cube prototypes.

stirred evenly. Then, add the curing agent in the ratio of 100:1 and stir evenly again. In addition, the order of preparation cannot be reversed because of the direct mixing of the curing agent, or the accelerator may cause fire. Next, the container

FIGURE 6: Devices for the silicone mold.

containing the resin was vacuumed in a vacuum machine, and the pressure was maintained at 0.06–0.08 MPa for 15–20 s. Then, the upper and lower silicone molds were accurately integrated through the connector after evenly spraying a layer of release agent inside them. Finally, the prepared resin was poured from one of the holes until the gap is filled completely, and the molded resin light guide body was taken out from the silicone molds after curing for two hours, as shown in Figure 8.

2.2.4. Embedding Cement Matrix. The self-compacting sand mortar that is prepared according to the mixing ratio (as shown in Table 1) was poured into the steel formwork (Figure 9(a)) which was placed with the preformed resin light guide body and fully vibrated on the shaking table. The RTMC block (Figure 9(b)) can be obtained by grinding and curing for 28 d after removing from the mold.

The RTMC panel of $200 \times 200 \times 20$ mm can be obtained by the same method (Figure 10(a)). The diameter of the light guide branch cross section was 15 mm, and the thickness of the connecting part was 6 mm (Figure 10(b)).

2.3. Testing Method for Light-Transmitting Property

2.3.1. Evaluation Index of Transmittance and Its Calculation Method. There are many performance indicators to be considered whether the transparency of material is good or not, such as transmittance, haze, refractive index, birefringence, and dispersion [27, 28]. In this paper, the transmittance was used to

FIGURE 7: Fabrication of the silicone mold. (a) Silicone top mold casting. (b) The upper and lower mold.

FIGURE 8: Resin light guide body.

FIGURE 9: Fabrication of RTMC block. (a) Pouring mould. (b) Resin translucent concrete block.

increase the transmission quality of RTMC. It can be directly calculated by the ratio of the incident energy and transmission energy of light expressed by the following equation:

$$T = \frac{W_1}{W_0} \times \frac{A_r}{A_t} \times 100\%, \quad (1)$$

where W_0 is the incident light energy; W_1 is the transmitted light energy; A_r is the section area of the transparent material; and A_t is the total area of the section of the product.

2.3.2. Experimental Devices. As shown in Figure 11, in the test, the LED floodlight was used as the light source. The Newport 2832-C dual-channel optical power meter and two 818-SL probes were adopted to measure the incident and

transmitted optical power of the test piece, respectively. In addition, the photosensitive area of the 818-SL probe was 1 cm^2 and the wavelength in the range of 400–1100 nm. The incident light energy and transmission light energy were read simultaneously. The light transmittance of the material can be obtained according to formula (1).

2.3.3. Testing Method for Optical Power

(1) The Zero Adjustment of the Probe. The premise of using the dual-channel optical power meter was that the initial states of the two channels were exactly the same. Therefore, the two probes need to be set to zero under the same light source condition before testing.

FIGURE 10: Fabrication of RTMC panel. (a) Equipment for making mold and the silicon mold. (b) Resin translucent concrete panel.

FIGURE 11: Devices of the transmittance test.

FIGURE 12: Transmittance test of RTMC.

(2) *The Positioning of the Probe and the Test Piece.* The two probes were placed on both sides of the test piece, respectively. Moreover, the photosensitive surface of the probe faces directed towards the side of the light source and was parallel to the front and back planes of the test piece.

(3) *The Positioning of Light Source.* To ensure that the light reaching the probe was approximately parallel light, it was known from the basic experiment that the light source needs to be placed on the vertical split line of the two probes. The distance of the light source was over two meters away from the probe, the measured transmittance tended to be stable. Therefore, in this experiment, the light source was about 3 meters away from the probe and was located on the vertical bisector line of the two probes (Figure 12).

2.4. Testing Method of Single-Axial Compressive Strength

2.4.1. Preparation of Specimens. The test blocks were made of $100 \times 100 \times 100$ mm, and the area ratio of resin were 1.13%, 2.0%, 3.62%, 4.54%, and 6.2%, respectively. Different types of light guide body were manufactured to study the influence of the light guide branch and the interface structure on the compression strength.

2.4.2. Testing Method of Compressive Strength. A certain concrete is poured in the formwork and fully vibrated on the shaking table. After 24 hours of room temperature curing, the mould was removed and then the specimens were cured

under standard curing conditions for 28 days with reference to the “Standard for Testing Methods for Mechanical Performance of Ordinary Concrete.” The compressive strength test was carried out on the specimens with the help of a pressure tester which had a measuring range of 3000 KN. Testing force can be loaded, kept, and unloaded automatically with controlling the displacement and the loading rate of 1 mm/min (Figure 13).

2.5. Testing Method of Thermal Performance

2.5.1. Experimental Devices. Thermal conductivity was obtained with the help of the equipment DRH-type thermal shield thermal conductivity tester (Figure 14). It was based on the principle of one-way stability and heat conduction. When the upper and lower sides of the test piece were in different stable temperature fields, the one-way heat flow flowed vertically through the plate-shaped test piece. The one-dimensional constant heat flux and the temperature of the hot and cold surface of the test piece were measured. Finally, the following formula was employed to calculate the thermal conductivity of the test piece:

$$\bar{\lambda} = \frac{Wd}{A(t_1 - t_2)}, \quad (2)$$

where W was the heat plate power (W); d was the thickness of the test block (m); A was the calculated area of the test block (m^2); t_1 was the temperature of the calorimetric plate ($^{\circ}\text{C}$); and t_2 was the temperature of the cold plate ($^{\circ}\text{C}$).

FIGURE 13: Pressure testing machine.

FIGURE 14: DRH-guarded hot plate thermal conductivity tester.

2.5.2. Preparation of Specimens. As a poor conductor of heat, the resin material possesses good thermal performance. The connecting part can not only connect light guide branches into a whole but also prevent heat transferring. As the tester requires the test piece with the thickness of 15–25 mm, the RTMC panel was made of $200 \times 200 \times 20$ mm. Then, the diameter of the light guide branch cross section was 15 mm and the thickness of the connecting part was 6 mm (Figure 15).

2.5.3. Testing Method of Experiment. Each type of test piece consisted of 3 pieces in a group, and all kinds of specimens

FIGURE 15: Panels needed for the experiment.

were tested successively. Firstly, turn on the power switch of cooling water to ensure the temperature of cold plate was 25°C , and the temperature of the hot plate was set to 40°C . Then, start the electric furnace to make the hot plate temperature reach the setting temperature. Finally, when the temperature was stable for about ten minutes, record the relevant data and substitute them into equation (2) to obtain the thermal conductivity of the test panel.

3. Results and Discussion

3.1. Results and Analysis of Light-Transmitting Property. The diameter of the resin cylindrical rod was 22 mm and the length was 20 mm, 60 mm, and 105 mm. The results of the light transmittance of the specimen under different wavelength conditions are shown in Figures 16–19.

From Figures 16 and 17, it can be seen that, in the range of 1000 nm, the incident light power and transmission light power decreases slowly with the wavelength in the range of 1000 nm and increases sharply with the wavelength over 1100 nm. This is because that nearly 70% of the radiation of the lamp is infrared, the radiation energy at the wavelength of 1100 nm is the strongest, and the optical power increases sharply. Thus, it can be seen that, in the visible light range, the light transmittance of the test specimens increased slowly with the wavelength. In the range of 1000 nm and increases significantly over the range of 1100 nm (Figure 18). Besides, from Figure 19, it can be found that the shorter the length of the light guide was, the higher the light transmission was. Furthermore, the light guide had excellent light transmittance which can be as high as 93% within the thickness of 100 mm and the light transmittance was 60% with the thickness exceeding 100 mm.

3.2. Results and Analysis of Compressive Strength

3.2.1. Analysis of Damage Morphology. Figures 20 and 21 show the compressive failure diagrams of plain concrete and RTMC, respectively. From Figure 20, it can be seen that the plain concrete block was pyramid-shaped due to the hoop

FIGURE 16: Relationship between the wavelength and incident optical power of specimens with different lengths.

FIGURE 18: Relationship between the wavelength and light transmittance of specimens with different lengths.

FIGURE 17: Relationship between the wavelength and transmitted light power of specimens with different lengths.

FIGURE 19: Effect of the specimen length on the light transmittance.

effect after concrete crushing and spalling. Instead, from Figure 21, the RTMC block remained good for integrity after failure and there was no large exfoliation and fragmentation on the surface of the specimen. The main reason was that the light guide body played the role of pulling the knot and winding mortar in the concrete.

3.2.2. Comparison and Analysis of Compressive Strength of Specimens under Different Contents of Resin. Table 3 shows the test axial pressure data of RTMC with different contents of resin. It can be seen from Figure 22 that when the area ratio was 4.54%, its strength reduced by 1.9%. When the area

ratio was 6.2%, the strength reduced by 3.5%. The main reason was that the large the resin volume ratio was, the large the interface area was, leading to crack rapidly along the interface, and the strength of the specimen will be reduced. So, the area ratio should be controlled within 5%, the influence of the embedded resin on the strength of the test piece was relatively small and the axial compressive strength of RTMC was close to that of plain concrete.

3.3. Results and Analysis of Thermal Performance

3.3.1. Results and Analysis of the Experiment Data. As shown in Figure 23, the thermal conductivity of the resin

FIGURE 20: Destructive form of plain concrete.

FIGURE 21: Destructive form of RTMC.

TABLE 3: Test axial pressure data of specimens with different contents of resin.

Area ratio (%)	0	1.13	2.0	3.62	4.54	6.2
Axial pressure (kN)	464.28	461.18	462.82	460.18	458.34	452.45
	460.12	463.43	458.44	456.34	454.67	448.79
	468.73	462.71	459.46	460.09	453.01	443.45
Average value (kN)	464.38	462.44	460.24	458.87	455.34	448.23

material was $0.1603 \text{ w/(m}\cdot\text{K)}$, which was close to $0.12 \text{ w/(m}\cdot\text{K)}$ of the thermal insulation material. The thermal conductivity of RTMC was $0.3815 \text{ w/(m}\cdot\text{K)}$ which was 60% lower than $0.89 \text{ w/(m}\cdot\text{K)}$ of plain concrete. This was because the resin light guiding body itself was the poor conductor of heat and it could prevent heat transferring well. Furthermore, the connection can not only link the light guide body as a whole but also block the transferring of heat.

3.3.2. Numerical Simulation on the Heat Transfer Performance

(1) *Establishment of the Finite Element Mode.* ANSYS software was adopted to establish the model of RTMC panel

FIGURE 22: Relationship between the area ratio and axial pressure of specimens.

FIGURE 23: Thermal conductivity of specimens.

and carried out the numerical analysis of heat transfer. Then, the selected unit was SOLID90 for the three-dimensional steady state and transient thermal analysis. As RTMC was composed of cement mortar and resin, the thermal conduction mainly occurred between the upper and lower surface of the panel. Thus, the analysis was simplified by only considering the one-dimensional heat conduction, and the finite element model of RTMC was shown in Figure 24. In accordance with the experimental process, the temperature load on the upper surface node of the model was set to 40°C and the load on the lower surface was set to 25°C (Figure 25).

(2) *Results and Analysis of Simulation.* According to Figure 26, the inner temperature of RTMC decreased from the top to the bottom, varying from 40°C to 25°C . The significant difference with the homogeneous material was that the temperature field was not of parallel layer distribution. It

FIGURE 24: Finite element model.

FIGURE 25: Temperature load loading model.

indicated that the resin material can well hinder the transferring of heat inside the panel.

As shown in Figure 27, the heat flux density in the mortar matrix area was significantly higher than the light guide body; the heat avoided the resin material and was collected in the mortar area. The main reason was that the thermal conductivity of cement mortar was much higher than that of resin material and the thermal resistance was relatively lower. This further explained that the existence of the resin material can greatly improve the thermal resistance of RTMC and make it have better function of heat preservation and insulation.

Figure 28 showed the temperature variation of RTMC in different areas along the thickness direction. The blue curve was temperature variation in the light guide branch area, and the decline rate did not change too much. The red curve was temperature variation in the mortar matrix area, which was divided into three stages: the first stage was in the upper mortar and the temperature dropped slowly from 40°C to 38°C; the second stage was the resin layer and the temperature dropped rapidly from 38°C to 27°C; the third stage was the same decline rate as the first stage from 27°C to 25°C. The main reason was that the thermal conductivity of the resin was obviously lower than the mortar, which can hinder more

heat transferring and result in the temperature of lower layer mortar much lower than the upper layer mortar.

(3) *Comparison of Experimental and Simulated Values of Thermal Conductivity.* The relationship between thermal flux and thermal conductivity of homogeneous material can be expressed as

$$\lambda_x = -\frac{q_x''}{(t_1 - t_2)/d}, \quad (3)$$

where q_x'' represents the heat flux density (W/m^2) in this direction.

RTMC was the heterogeneous material and different location nodes have different heat flux values. Therefore, the average thermal conductivity can be obtained by the average of heat flux of each node, and the value $\bar{q}_x''$ of RTMC can be calculated as $0.2653 \text{ W}/\text{m}^2$. The value $\bar{\lambda}_x$ can be obtained as $0.3537 \text{ w}/(\text{m}\cdot\text{K})$ with formula (3). Comparing the experimental value $0.3815 \text{ w}/(\text{m}\cdot\text{K})$, it was found that the simulated value was close to the measured value and the error was within 8%. It showed that the simulation results were effectiveness and feasibility and the model can be used in the evaluation of thermal performance of RTMC.

3.4. Microstructure Analysis of RTMC. The microstructure of RTMC was studied by SEM as shown in Figure 29. Figure 29(a) was the image of the self-compacted concrete matrix from which it can be found that the microscopic structure was featured with small apertures, less harmful pores, and high density. The reason was that the compaction of fly ash can reduce the pore volume and fill the pores in the slurry which was extremely beneficial to the durability of concrete. Figure 29(b) shows the interface between the resin and the matrix which indicated both of the two parts were much closely combined. Due to the plasticity of the resin translucent body, the surface of the resin translucent body can be made more rough so as to enhance the adhesion of resin with matrix and improve the durability of the concrete.

4. Conclusions

- (1) Taking transparent resin and self-compacting mortar as raw materials, a new novel light-transmitting concrete product, RTMC, was developed by using self-designed production equipment and production technology. The whole process was characterized by low production cost and high production efficiency.
- (2) The light-transmitting properties of RTMC were measured by using an optical power meter. The resin material had excellent light transmittance within the thickness of 100 mm which can be as high as 93%, and the light transmittance was 60% with the thickness exceeding 100 mm.

FIGURE 26: Overall temperature distribution diagram (°C).

FIGURE 27: Overall heat flux density distribution diagram ($J/(m^2 \cdot s)$).

FIGURE 28: Overall temperature distribution diagram.

(3) The compressive strength of RTMC decreased with the increase of content of the resin. When the area ratio was within 5%, the compressive strength of resin concrete was close to plain concrete.

(4) RTMC had excellent thermal performance that the thermal conductivity of RTCM was $0.3815 \text{ w/(m}\cdot\text{K)}$, which was 60% lower than $0.89 \text{ w/(m}\cdot\text{K)}$ of plain concrete. The ANSYS simulation results of thermal

FIGURE 29: SEM images of RTMC. (a) The self-compacted concrete matrix. (b) Resin/matrix interface.

performance were effectiveness and feasibility, and the model can be used in the evaluation of thermal performance of RTMC.

- (5) The SEM of RTMC demonstrated that the micro-structure of the matrix not only had small apertures and less harmful pores but also high density; the entire surface of resin was reasonably rough and can be well meshed with the matrix.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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