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Mechanical and thermal insulation properties of clay-based lightweight concrete

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ABSTRACT

Building materials production and residential heating will consume a lot of energy and emit a lot of CO_2. Using ceramsite to prepare lightweight concrete with excellent thermal insulation performance and using calcined clay to replace part of Portland cement in concrete preparation can greatly reduce energy consumption. In this study, shale ceramsite and pottery sand were used as coarse aggregate and fine aggregate respectively to prepare lightweight concrete. First, the optimal volume sand ratio was determined. Then, the dosages of calcined clay and limestone from 30%, 50% to 70% were used. The effects of calcined clay and limestone content on the microstructure, mechanical properties and thermal insulation properties of concrete were studied. The results showed that the optimum volume sand ratio was 50%. When the dosage of calcined clay and limestone was 30%, the strength were the highest at all ages, and the strength at 28 days could reach 33.6 MPa, which was 12% higher than that of the control group. When the replacement level continued to increase, the strength at all ages began to decline. The thermal conductivity of the prepared clay-based lightweight concrete was as low as 0.144 W/mK, exhibiting the excellent thermal insulation performance. The lightweight concrete prepared in this study showed high strength and excellent thermal insulation performance, and thus had a good application prospect.

1. INTRODUCTION

Construction industry accounts for about 39% of global energy consumption and about 38% of global greenhouse gas emissions [1]. In addition to building materials production, building heating and refrigerating will also emit huge amount of CO_2. In the year of 2018, 38% of China's CO_2 emissions came from residential heating [2]. Therefore, there are two ways to reduce building energy consumption and CO_2 emissions. On the one hand, various industrial solid wastes or cementitious materials with lower calcination temperature, e.g. calcined clay, can be used as alternative cementing materials. The temperature for producing calcined clay is around 700℃ [3]. Using calcined clay and limestone powder to replace part of Portland cement, known as Limestone Calcined Clay Cement (LC^3) can greatly reduce energy consumption. And when the replacement level is 50%, LC3 can achieve mechanical properties similar to Portland cement [4].

On the other hand, the use of thermal insulation materials for building envelope can greatly reduce the energy consumption of buildings. At present, the thermal insulation materials mainly include organic materials such as polystyrene board and inorganic materials such as foamed concrete and lightweight concrete. Among them, organic thermal insulation materials are generally flammable and have poor stability [5,6,7], and the equal strength of foamed concrete is too low. Thus, lightweight concrete is more likely to achieve higher strength and durability.

Shale ceramsite is porous, which can not only achieve internal maintenance, but also undergo pozzolanic reaction [8,9], further strengthening the interface transition zone. However, the interlayer structure of calcined clay prevents water molecules from entering, and can maintain good thermal insulation performance. Using calcined clay instead of cement can greatly reduce the thermal conductivity of concrete, which can be reduced by 40%[10]. Therefore, in this paper, shale ceramsite was used as coarse aggregate, and shale pottery sand was used as fine aggregate to prepare lightweight concrete. First, the optimal volume sand ratio was determined. Then 30 wt.%, 50 wt.% and 70 wt.% of calcined clay and limestone were used to replace Portland cement to study the effects of the replacement amount of calcined clay and limestone powder on the microstructure, strength and thermal insulation of concrete.

2. Material and Methods

2. 1 Material

P.I 42.5 Ordinary Portland Cement, calcined clay, limestone powder, gypsum, pottery sand, shale ceramsite and superplasticizer were used in this study for preparing lightweight concrete. Among them, the particle size of calcined clay is below 6000 mesh, and the particle size of gypsum and limestone powder is below 200 mesh. The densities of pottery sand and shale ceramsite were 1.3 kg/m^3 and 0.8 kg/m^3, respectively. The 24-hour saturated surface dry absorption of LWFA was determined to be 10% by mass, and the porosity of pottery is 35~40%. The metakaolin content of the calcined clay was about 50%. The solid content of superplasticizer was65%.

Table 1. Chemical composition of shale ceramsite, pottery sand and calcined clay (wt.%)

Composition	SiO2	Al2O3	Fe2O3	K2O	Na2O	MgO	TiO2	CaO	LOI	numerical tube Pressure(MPa)
Ceramsite	60.88	20.00	8.10	4.5	1.19	3.01	0.93	0.61	/	1.0
Pottery sand	62.54	19.46	7.25	4.58	1.19	2.91	0.80	0.56	/	/
Calcined clay	50.02	45.70	0.53	0.13	0.18	0.12	1.52	0.17	1.09	/

Table 1 lists the chemical compositions of shale ceramsite and pottery sand, and Figure 1 shows the XRD patterns of shale ceramsite and pottery sand. It can be seen that their chemical compositions were similar, with quarz, magnesia-alumina spinel and some amorphous phases.

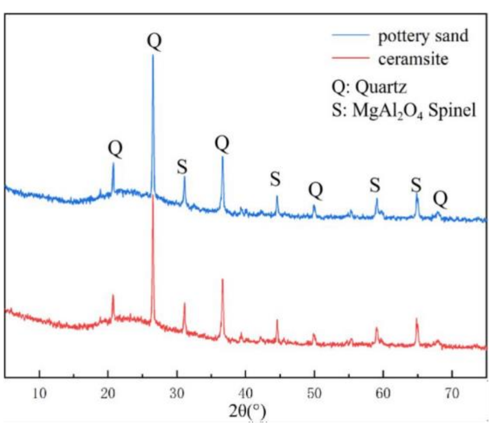

Figure 1. XRD spectra of shale ceramsite and pottery sand.

2. 2 Methods

Determination of volume sand ratio

To determine the optimal volume sand ratio in the system, the mix proportions in Table 2 were adopted, where the volume sand ratio varied from 30%, 40%, 50%, 60% to 70%. The compressive strength at 3 days, 7 days and 28 days were tested, and the results are shown in Figure 2. It can be clearly seen that with the increase of volume sand ratio, the strength of each age gradually increased. On the one hand, because the pottery sand particles were finer, they can fill the pores due to the accumulation of ceramsite to achieve a more compact accumulation. On the other hand, ceramsite was more brittle and more easily crushed than pottery sand, so the compressive strength was gradually increasing with the increase of volume sand ratio, but at the same time, it also increases the density and thermal conductivity, and when the volume sand ratio is greater than 50%, the cement paste can not completely wrap the aggregate. It can be seen that when the volume sand ratio was greater than 50%, the increase rate of compressivestrength had begun to slow down, which indicated that the compact accumulation was achieved, and the compressive strength exceeded 30 MPa at this time, so the optimal volume sand ratio was 50%.

Table 2. Mix proportions of lightweight concrete with different volume sand ratio (kg/m^3)

No.	Cement	pottery sand	ceramsite	Water
VR30	450	264.1	399.6	180
VR40	450	352.1	342.5	180
VR50	450	440.1	285.4	180
VR60	450	528.2	228.3	180
VR70	450	616.2	171.2	180

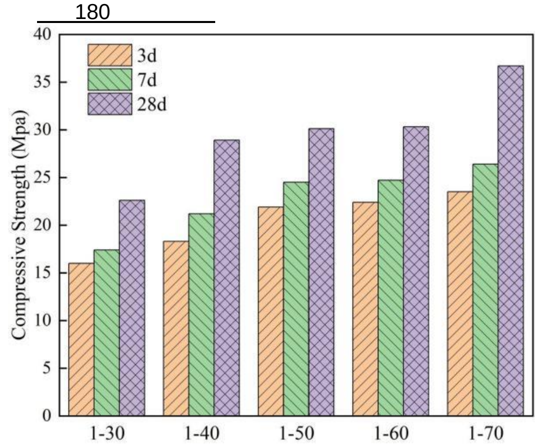

Figure 2. Compressive strength of lightweight concrete with different volume sand ratios.

2. 2. 2 Specimen preparation

In this study, four groups of lightweight concrete samples were prepared. One group used ordinary Portland cement as blank group, the other three groups used calcined clay and limestone to replace cement with the replacement levels of 30%, 50% and 70%. The volume ratio of sand was fixed as 50% according the determined optimal volume sand ratio. The sample mix ratios are shown in Table 3. The raw materials were mechanically mixed and then casted into the molds. After that, the samples were sealed at room temperature for 24 hours, and finally, the samples were demoulded and put into a standard curing room (temperature 20 2℃, humidity ≥95%) for 3, 7 and 28 days, respectively.

Table 3. Mix proportions of concrete (kg/m^3)

No.	Cement	Gypsum	Calcined clay	Limestone powder	Pottery sand	Ceramsite	Water	SP
PC00	450	0	0	0	440.1	285.4	180	0
LC30	306	9	98.3	36.7	440.1	285.4	180	3.4
LC50	216	9	163.8	61.2	440.1	285.4	180	4.5
LC70	126	9	229.3	85.7	440.1	285.4	180	5.5

2. 2. 3Testing methods

The compressive strength test of concrete was performed on the 100 × 100 × 100 mm3 samples according to the standard GB/T50081-2002.

The X-ray diffraction (XRD) spectra were tested by a Panalytical Empyrean X-ray diffractometer with Cu-kα (λ = 1.54 Å), the diffraction angle (2 θ) was 15-60 ° , and the scanning speed was 5 °/min.

The equipment used for Thermogravimetric analysis (TGA) was STA449F3 comprehensive thermal analyzer manufactured by NETZSCH Scientific Instruments Trading Ltd. The test temperature was from room temperature to 1000 ℃, the heating rate was 10 ℃ /min, and the test was conducted in nitrogen atmosphere.

The samples at 28 days with the size of 300×300 × 30 mm3 was dried to a constant weight, and then their thermal conductivities were tested by TPS2500S thermal constant analyzer.

3. RESULTS AND DISCUSSION

3. 1 Compressive strength

Figure 3 shows the compressive strength of four groups of lightweight concrete. Figure 3 shows when the dosage of calcined clay and limestone was 30%, the strength at all ages were higher than that of the control group, and the strength at 28 days was 33.6 MPa, which was 12% higher than that of control group. The strength of LC50 group at 3 days and 7 days were slightly higher than that of control group, while that of LC50 group on 28th day was lower than that of control group, indicating that its strength development was hindered. However, the strength of LC70 group decreased greatly at each age, which indicated that the replacement level of calcined clay and limestone were so high that the mechanical properties of lightweight concrete would be decreased.

3. 2 XRD

Figure 4 shows the XRD spectra of four groups of samples. It can be clearly seen from the figure that the diffraction peaks of calcium hydroxide in LC30 and PC00 control groups were strong, while the peaks of calcium hydroxide in LC50 and LC70 groups were weak. The reaction of calcined clay consumed calcium hydroxide, and there was enough calcium hydroxide in LC30 group for supporting its reaction, so its strength develops well, while the calcium hydroxide provided by cement in LC50 and LC70 groups was not enough to support the hydration of all calcined clay, so the strength development was hindered.

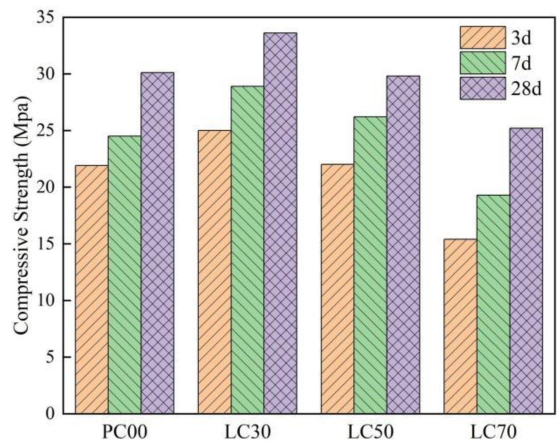

Figure 3. Compressive strength of four groups of concrete with different proportions.

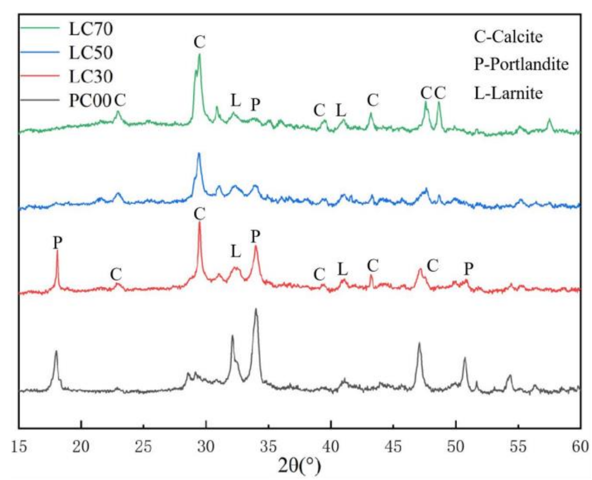

Figure 4. The XRD pattern of cement paste with four groups of different proportions.

3. 3 TGA

Figure 5 shows the TGA curves of four groups of samples. The endothermic peak of calcium hydroxide is around 400 ℃. It can be seen that the content of calcium hydroxide in PC00 group is highest, and the consumption of calcium hydroxide increased with the increase of replacement level. LC30 group also contained some calcium hydroxide,which indicated that its calcined clay can react continuously, so its strength development was best, while in LC70 group, the endothermic peak of calcium hydroxide almost disappeared, which indicated that there were still surplus calcined clay and limestone powder that were not involved in the reaction, and also corresponded well to their strength development. Although calcium hydroxide still existed in LC50 group, its content was too small to meet the subsequent reaction of calcined clay, which also showed that the optimal replacement level should be between 30% and 50%.

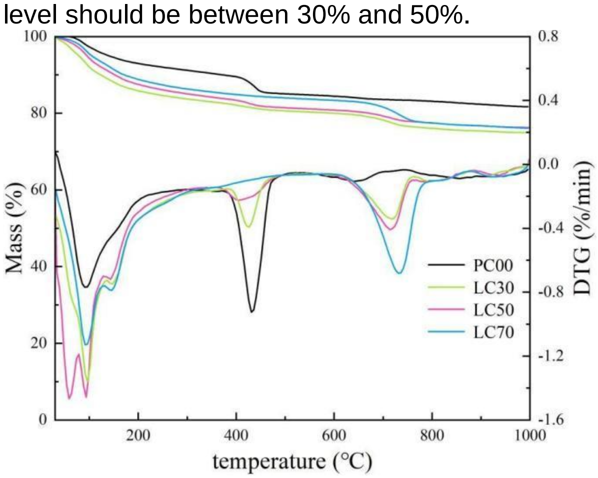

Figure 5. The TGA curves of four groups of samples

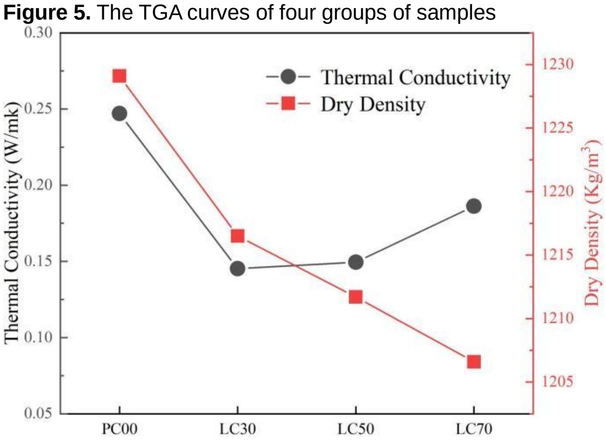

Figure 6. Thermal conductivities and dry densities of four groups of lightweight concrete slabs with different proportions.

3. 4 Thermal conductivity

Figure 6 shows the thermal conductivities of four groups of concrete slabs. The thermal conductivity of PC00 group was 0.247 W/mK, and those of LC30, LC50 and LC70 group were 0.1452 W/mK, 0.1495 W/mK and 0.1863 W/mK, respectively. The increase in calcined clay content does not contribute to the improvement of thermal insulation performance, which is similar to the results in the literature. The thermal conductivity of ordinary concrete was 1.6 W/mK. The thermal conductivity of lightweight concrete prepared in this study was greatly reduced, and it had good thermal insulation performance. After using calcined clay and limestone, the thermal conductivity further decreased, and LC30 group had the lowest thermal conductivity, but the density of the three groups was not much different, which indicated that when the replacement level was 30%, the accumulation was so dense. When the content of calcined clay increased, the accumulation would be more compact and the structure would be denser because of the smaller particle size of calcined clay, and the porosity would decrease, so the thermal conductivity would increase.

4. CONCLUSION

In this study, shale ceramsite was used as coarse aggregate and shale pottery sand was used as fine aggregate to prepare lightweight concrete. The influence of volume sand ratio on its compressive strength was studied, and the influence of different content of calcined clay and limestone on the mechanical properties, microstructure and insulation properties of lightweight concrete was explored. The conclusions are as follows:

With the volume sand ratio increasing from 30% to 70%, the compressive strength was gradually increasing, but the increase of the compressive strength slowed down when it was greater than 50%, which showed that the optimal volume sand ratio was 50%.

When the dosage of calcined clay and limestone was 30%, its strength at all ages was the highest, and the strength at 28 days was 33.6 MPa, which was 12% higher than that of the control group. When the dosage continued to increase, the strength at all agesbegan to decline.

When the replacement level was 30%, the $Ca(OH)_2$ produced by cement hydration could meet the hydration of calcined clay at this time, which could play a good role in synergistic reaction. When the dosage increased, $Ca(OH)_2$ produced by hydration was not enough to support the later reaction of calcined clay, which also led to the decrease of its strength.

When the replacement level was 30%, the lowest thermal conductivity is 0.1452 W/mK, but the thermal conductivity of the four groups was less than one- sixth of that of ordinary concrete, exhibiting itself good thermal insulation performance. When the dosage further increased, its thermal conductivity began to increase, indicating that its pores began to decrease and the structure was more densely packed.

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