Thermal conductivity of cement stabilized earth blocks

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Abstract

The present study examines the effect of bulk density and cement content on the thermal conductivity of cement stabilized earth blocks (CSEB). The experimental results show that the thermal conductivity increases as a function of bulk density; changes in cement content result in a small variation in thermal conductivity of CSEB at a given bulk density. No obvious linear relationship between the thermal conductivity and cement content of CSEB has been observed. However, a significant increase of compressive strength of CSEB caused by the addition of cement has been observed; moreover, the compressive strength of CSEB increases with increasing cement content. CSEB show potential in earth buildings due to their improved compressive strength and reduced thermal conductivity.

Keywords

Thermal conductivity; Earth material; Cement; Cement stabilized earth block; CSEB.

Highlights:

- Thermal conductivity of cement stabilized earth blocks (CSEB) increases with bulk density.

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- Thermal conductivity of CSEB slightly varies with the addition of cement.
- Compressive strength of CSEB increases with increasing cement content.

1. Introduction

Along with the development of both rural villages and cities in China, which is the fastest growing economy in the world, the progressive increase in the demand of residential buildings requires a huge building materials to be prepared and used. Nowadays, energy shortage and pollution have become the main problems in the society, the modern building materials which have high energy costs and CO_2 emissions should be replaced by the sustainable and environmental building materials which are abundant and inexpensive. Earth construction, which is warm in winter and cool in summer, is one of the oldest and most widespread buildings in human history. It can contribute to improve living comfort and reduce environmental problems.

Earth blocks are one of the earth building techniques and have widely been used in China. Its abundant source benefits from direct site-to-service application to reduce the costs caused by acquisition, transportation and production [1]. No specialized instrument and specific surroundings are required during the production. In addition, earth buildings provide good sound and thermal insulation, and they may also help in regulating the indoor humidity [2]. Unfortunately, earth materials have been ignored for many years in the modern construction sector; this is mainly due to the lack of strength and durability. The compressive strength represents the load-bearing performance of earth blocks; lower compressive strength means earth blocks can only be used for self-bearing members and the storey of building has been restricted. The lack of durability leads to earth buildings are vulnerable to weathering and rainfall and regular repair will cost human and financial resources. In recent years, a growing interest in overcoming the mechanical defects has been appeared and the technique of stabilization has been used in order to enhance the durability and compressive strength of earth blocks. Bahar et al. [3-4]

conducted experimental studies to present the effect of stabilization methods on mechanical properties. The results indicated that the combination of compaction and cement stabilization is an effective choice for increasing strength of earth blocks. Amoudi et al. [1,5-6] carried out a series of experiments on mechanical properties of cement stabilized earth blocks (CSEB); the results showed that cement in the presence of water tends to form hydration products in order to wrap the soil particles and occupy the voids. The compressive strength, dimensional stability, total water absorption and durability were improved significantly and thus became technically acceptable. Heathcote [7] presented that there was a strong relationship between mechanical properties and cement content. The compressive strength, modulus and durability were enhanced by increasing cement content [8-10]. The thermal insulation of earth buildings provides a comfortable environment for residents in order to reduce heating and cooling energy consumption. Compared with the mechanical properties, fewer studies on the thermal property of CSEB have been reported so far. Adam and Jones [11] measured the thermal conductivity of lime/cement stabilized hollow and plain earth blocks by the guarded hot box method; the results indicated that the thermal conductivity is highest for cement stabilized soil building blocks. Ashour et al. [12] measured the thermal conductivity of earth bricks consisting of soil, cement, gypsum and straw; the results showed that the addition of fibre positively improved the thermal property and the thermal conductivity slightly increased with cement content.

In this context, this study reports an experimental investigation to evaluate the effect of both bulk density and cement content on the porosity of CSEB and consequently on the thermal conductivity. Microstructure of CSEB has been pictured to assist the analysis of correlation between bulk density/cement content and porosity. The aims of this study are to guide the manufacturing for low thermal conductivity and sufficient compressive strength CSEB in the process of earth construction.

2. Experimental

2.1. Materials

2.1.1. Soil

The soil used in this study was collected from Turpan of Xinjiang Uygur Autonomous Region. The grading curve and the particle size of the soil were determined by grain size analysis, according to GB/T 50123-1999 [13]. The test results are presented in Fig. 1. The Atterberg limits of the soil are: Liquid limit (LL=23.7 %) and plasticity index (PI=5.5 %). X-ray diffraction analysis determines the mineralogical composition, as shown in Fig. 2. The results show that the CSEB soil includes quartz (SiO_2), calcite ($CaCO_3$), anorthite ($CaAl_2Si_2O_8$) and albite ($NaAlSi_3O_8$) minerals. Chemical composition of the soil is shown in Table 1, the chemical composition analysis is on the basis of x-ray fluorescence.

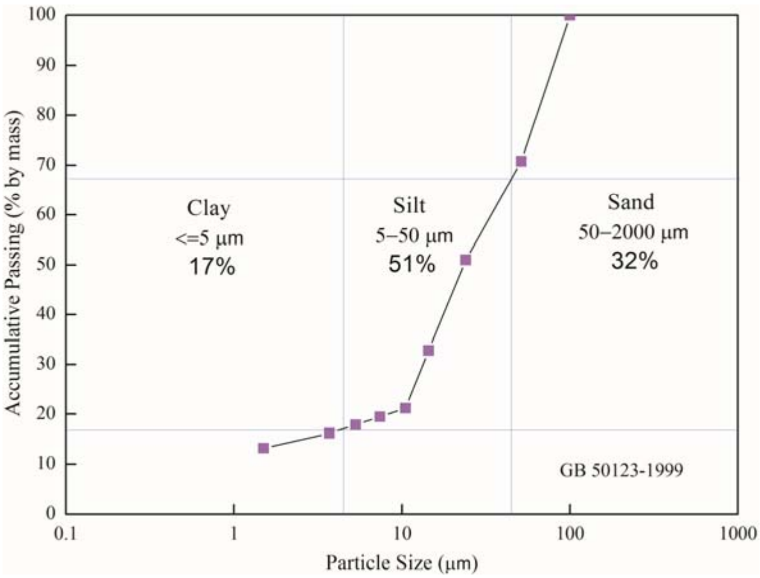

Fig. 1. Grain size distribution of soil used.

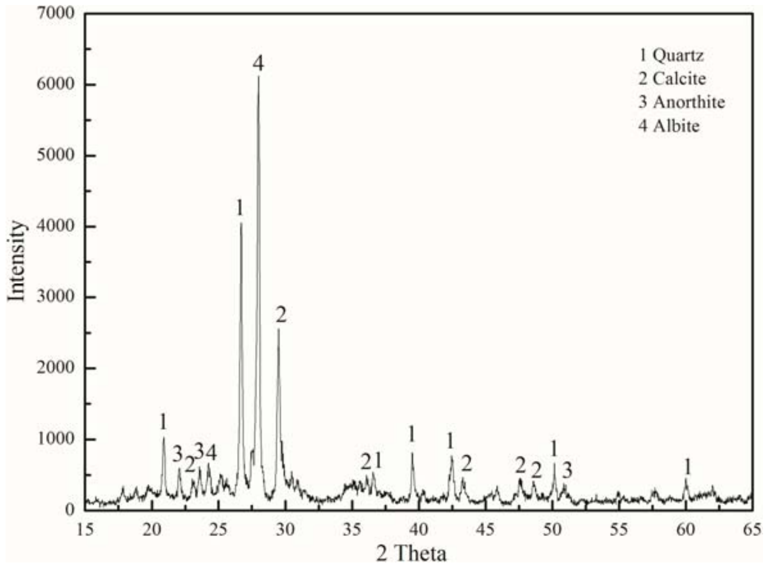

Fig. 2. X-ray diffraction of soil used.

Table. 1. Chemical composition of soil used (wt%).

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	MnO	ZrO_2
47.770	12.210	8.845	19.367	4.261	3.980	1.940	0.454	0.860	0.231	0.082

2.1.2. Cement

In this study, Portland cement was used as stabilizer for production of cement stabilized earth blocks (CSEB). The Portland cement used complied with GB 175-2007 P O 42.5 grade [14], equivalent to CEM II/A-M(S-V) 42.5 N according to BS EN 197-1 [15]. As this cement has enough strength after hydration to enhance the compressive strength of CSEB [16], it was used in our work. Also, this cement is widely used in the construction industry, i.e. supporting the choice of material composition in our research.. The chemical composition of the Portland cement is presented in Table 2.

Table. 2. Chemical composition of the Portland cement (wt%).

SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	SO_3	P_2O_5	Na_2O	MnO	TiO_2	Ignition loss
20.65	62.23	3.15	3.27	1.65	0.76	0.05	0.48	0.07	0.16	2.67

2.2. Cement stabilized earth block

Before preparation of stabilized earth samples, the soil was sieved to remove the oversized particles (2 mm). The sieved soil was dried in air at 105 ºC for 24 hours. The dried soil and cement were mixed at different ratios between soil and cement (97:3, 95:5, 93:7 and 91:9), the ratio and amounts of materials were controlled by weights. Water was added at a content of 13 wt% to mass mixture and mixed for 10 minutes until the mixture was uniform by wetness. Samples were prepared by a hydraulic press, as shown in Fig. 3. The mixture was compacted at different bulk densities and the classification of bulk density includes 1.5, 1.7, 1.9 and 2.1 g/cm^3. The bulk density can be identified by mass of mixture pressed into the mould divided by volume of samples. Two groups of sample dimensions were selected according to the purpose of the testing to be carried out. The dimensions of the samples which were used for thermal conductivity tests were 50 mm × 50 mm × 25 mm, while the dimensions for both compressive strength and bulk density tests were 50 mm × 50 mm × 50 mm.

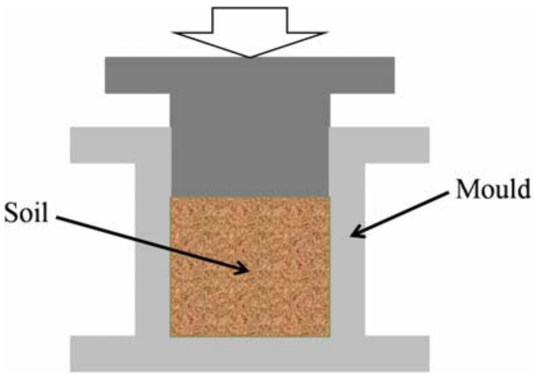

Fig. 3. Process of compaction of specimens.

Samples were wrapped with plastic foils to assure the cement hydration and placed in the laboratory for 28 days. The temperature and relative humidity (RH) in the laboratory were 20 ± 1 ºC and 60 ± 1 % RH.

2.3. Characterization

2.3.1. Thermal conductivity

The thermal conductivity was measured by using a Hot Disk apparatus (TPS-2500 S) which was calibrated with an expanded polystyrene board in order to ensure the accuracy of the experimental results. Each measurement was repeated three times and the mean value was reported. Before the measurement, flatness of specimens was checked in order to make a good contact between the sensor and the sample. During the measurements, a sensor probe was placed between two specimens, as shown in Fig. 4.

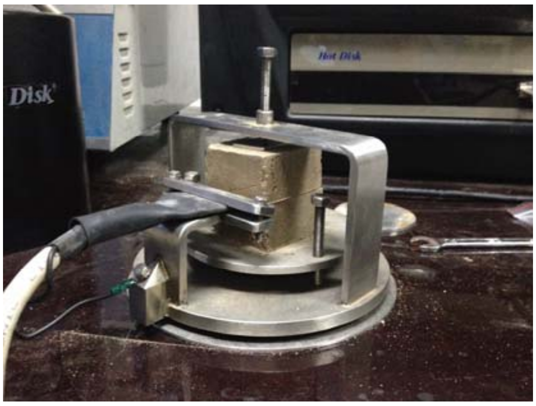

Fig. 4. Experimental setup for thermal conductivity measurements by using Hot Disk apparatus.

2.3.2. Porosity

The porosity values of CSEB were determined by Le Chatelier Flask, according to GB/T 208-2014 [17]. In order to obtain porosity values of CSEB at different bulk density and cement content values, the CSEB examples were broken and grinded into powder by both mortar and pestle after thermal conductivity testing. The mass percentage of the small-sized particles increased after grinding. The CSEB powder was placed in an oven at 105 ºC for 24 hours.

First, anhydrous kerosene was poured into Le Chatelier Flask until liquid level reached a certain scale between 0 and 1 mL. Le Chatelier Flask was stuffed by cap and put into thermostatic water bath for 30 min at a certain temperature of 20 ºC. The volume of anhydrous kerosene is denoted V_1. Then, a mass m of dried powder was loaded into anhydrous kerosene and Le Chatelier Flask was wobbled until all air escaped from the liquid. Le Chatelier Flask was put into thermostatic water bath for 30 min again and the scale (V_2) was recorded. Porosity of CSEB was then calculated by using the following equations [17]:

$$\rho_{powder} = \frac{m}{V_2 - V_1} \tag{1}$$

$$\rho_{CSEB} = \frac{m}{V_{CSEB}} \tag{2}$$

$$\varepsilon = 1 - \frac{\rho_{CSEB}}{\rho_{powder}} = 1 - \frac{V_2 - V_1}{V_{CSEB}} \tag{3}$$

where ρ_{powder} is the density of CSEB powder [g/cm^3], m is the mass of CSEB [g], V_1 is the volume of anhydrous kerosene [ml], V_2 is the volume sum of anhydrous kerosene and CSEB powder [ml], ρ_{CSEB} is the bulk density of CSEB [g/cm^3], V_{CSEB} is the volume of CSEB [ml] and ε is the porosity of CSEB [%].

2.3.3. Compressive strength

At the present stage, the samples were prepared as cylinders [18-19], prisms [4, 20] and cubes [10, 21-22] for compressive strength tests. There is no consistent rule for the selection of sample shapes and dimensions worldwide. Combining with actual conditions, a 50 mm × 50 mm × 50 mm cubic sample was selected for compressive strength tests in this study. The compressive strength test of cubic samples were performed by a hydraulic test machine having a testing capacity of 60 kN according to GB/T 50081-2002 [23], equivalent to BS 1924-2:1990 [24]. The rate of compression was set at 3 N/mm^2/min. For each cement content and each bulk density, three samples were tested as replicates. The compressive strength was calculated from the compression force and cross-sectional area of the cube:

$$P = \frac{p}{A} \tag{4}$$

where P is the compressive strength [MPa], p is the maximum compression force [kN] and A is the cross-sectional area of the cubic sample [mm^2].

Friction between the sample and the platens confines the lateral deformation of the sample during the compression leads to an apparent increase in compressive strength. Determining the compressive strength, a height to thickness correction factor was applied to account for the effects of platen restraint [25]. The compressive strength of CSEB was equal to the compressive strength test values multiplied by the correction factor (0.70) as the height/thickness ratio of sample in this study was 1.0 [26].

3. Results and discussion

3.1 The effect of bulk density on thermal conductivity

A correlation exists between bulk density, porosity and thermal conductivity, which has been presented by an experimental method by Mansour et al [27]. Thermal conductivity of earth blocks is impacted by porosity variation which is caused by differences in bulk density. As shown in Fig. 5, there is a linear correlation between the bulk density and the porosity at different cement contents, where the porosity of CSEB decreases as the bulk density increases. This is fairly understandable since CSEB can be considered as a two-phase composites, i.e. solid (soil and cement) and air, and increasing the solid content will increase the bulk density and decreases the porosity at the same time. In general, the porosity is decreased by a factor between 2 and 3 as the bulk density is increased from 1.5 to 2.1 g/cm^3. The cement content shows however no obvious effect on the density-porosity relationship, which is probably due to the similar density of cement and earth material used in this study.

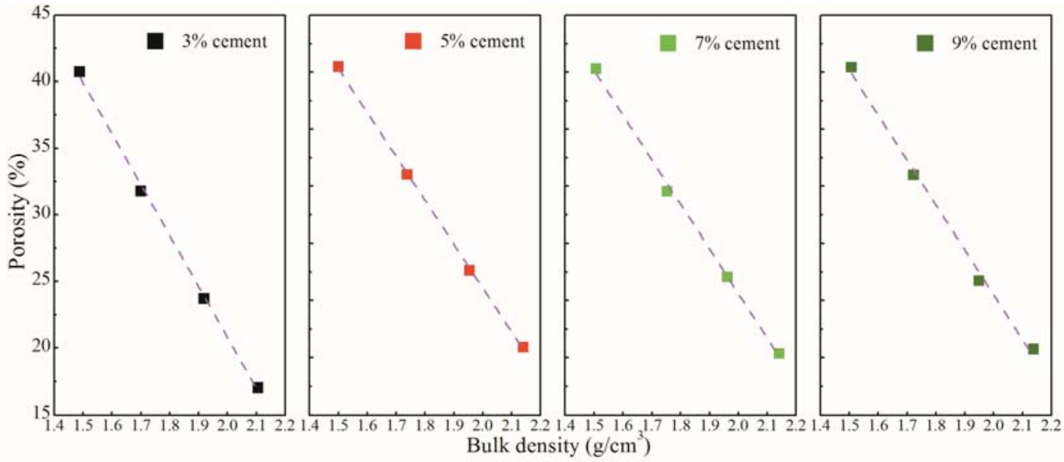

Fig. 5 Relationship between porosity and bulk density for different cement contents.

The microstructure of CSEB with 9 wt% cement for different bulk density values can be seen in Fig. 6. The matrix of CSEB with 9 wt% cement becomes more and more compact with increasing bulk density. When the bulk density increases from 1.5 g/cm^3 to 2.1 g/cm^3, the quantity of pore reduces gradually and the pore diameter decreases significantly. When the bulk density is 2.1 g/cm^3, the larger pores barely exist in the CSEB. Increasing bulk density improves the compactness inside the matrix, which leads to a decrease of porosity with increasing density.

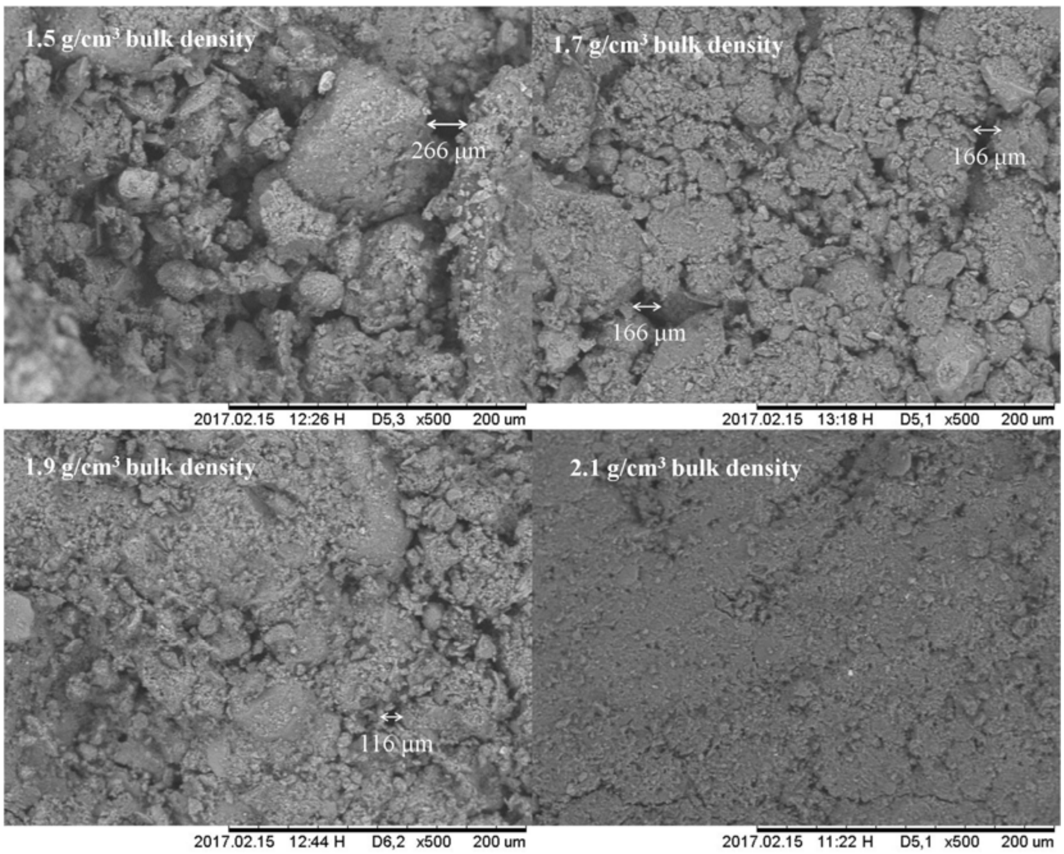

Fig .6 SEM images of cement stabilized earth blocks for different bulk densities.

The thermal conductivity values of CSEB have been measured by using a Hot Disk apparatus as described earlier. The influence of bulk density on thermal conductivity at different cement content values are shown in Fig. 7. The mean values of the CSEB thermal conductivity are reported with the uncertainty calculated as the standard deviation of the mean. The values obtained from the thermal conductivity testing are relatively concentrated (the standard deviation values range between 0.004 and 0.025).

The variation of thermal conductivity is a linear function of the bulk density for different cement contents. The thermal conductivity of CSEB increases with increasing bulk density. The results confirm the general laws of thermal conductivity for porous materials and this phenomenon for earth blocks is similar as in the studies of Tang et al. [28] and Taallah et al. [29].

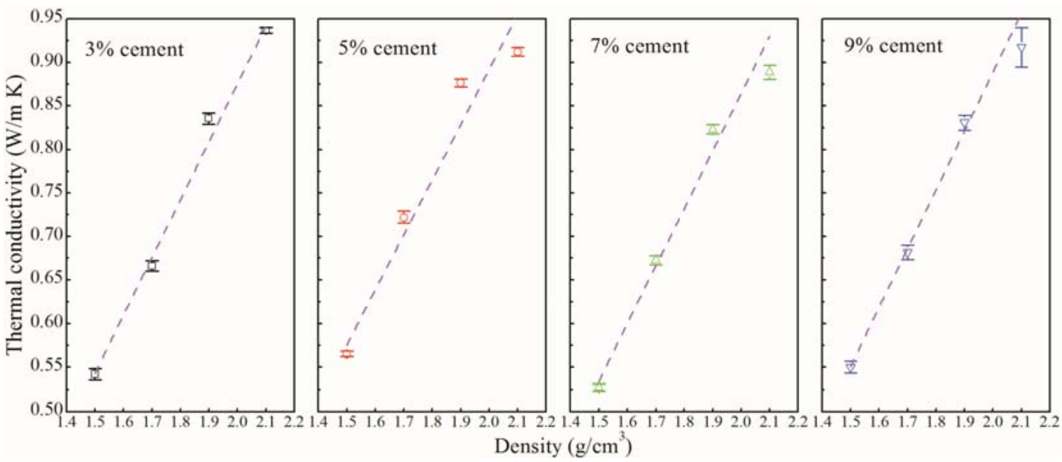

Fig. 7 Thermal conductivity vs. bulk density for different cement contents.

It can be seen in both Fig. 5 and Fig. 7, as the bulk density of the sample increases, the porosity decreases and then the thermal conductivity increases. The dependence of the thermal conductivity of CSEB bulk density can be explained by the porosity of the samples. The effect of porosity of CSEB on the thermal conductivity is presented in Fig. 8.

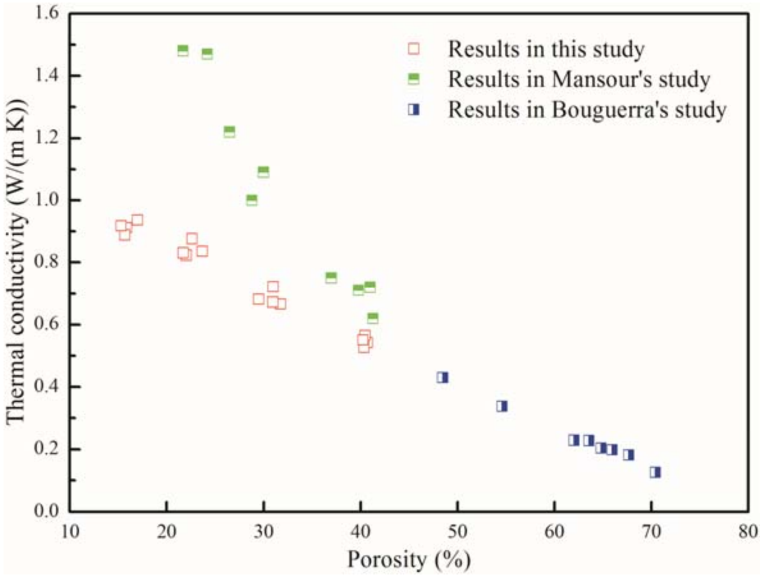

Fig. 8 Variation of thermal conductivity as a function of porosity.

As shown in Fig. 8, the thermal conductivity decreases linearly with increasing porosity. A CSEB belongs to porous material and consists of a solid phase and air when the material is dry. Air has a very low thermal conductivity of about 0.026 W/(m K), compared to between 0.5291 and 0.9365 W/(m K) for CSEB. Heat transfer will be reduced by the introduction of air inside the matrix as the thermal conductivity of air is an order magnitude lower than for CSEB; increasing the porosity means more air inside the samples hence leading to a decrease in the thermal conductivity. Similar results have been reported previously in the studies of Mansour et al. [27], Guillaud et al. [30] and Bouguerra et al. [31].

At a given porosity value, the thermal conductivity of CSEB in this study is lower than that reported by Mansour et al. [27]. It is noticeable that the sand content of soil used in our study is 32.00 wt%, which is less than 39.11 wt% as stated in Mansour et al.'s study. The difference of mineral composition generates a distinction in thermal conductivity, as quartz is the main mineral of sand and gravel and the thermal conductivity of quartz (7.7 W/(m K)) is much higher than of other minerals, i.e. the content of quartz may significantly impact the thermal conductivity of CSEB. Therefore, the thermal conductivity of CSEB in our study is lower than that in Mansour et al.'s study. In addition, the slope of fitting line of our study is smaller than Mansour et al.'s, which means the thermal conductivity varies slightly more than in the results by Mansour et al. at the same increase of porosity. This phenomenon can also be interpreted by the difference in the thermal conductivity caused by mineral composition distinction. Because the quartz content of material used by Mansour et al. was much higher than that in our study, a more significant reduction of the quartz mass for the same increasing porosity in the work by Mansour et al. [27] leads to a more obvious reduction of the thermal conductivity. Compared with the above discussion, the materials analyzed by Bouguerra et al. [31] have much higher porosity values and much lower thermal conductivity. It may be explained by addition of wood aggregates, which demonstrate a kind of tubular structure and are able to outstandingly increase the porosity of the composite materials.

3.2 The effect of cement content on thermal conductivity

Similar to the study concerning the relationship between thermal conductivity and bulk density, the effect of cement content on thermal conductivity can be analyzed by porosity variation caused by differences in cement content. Relationship between porosity and cement content of CSEB is shown in Fig. 9. At different bulk densities, the porosity decreases to some extent slightly with increasing cement content. According to the results in Chapter 3.1, the presence of pores filled with air decreases the thermal conductivity of CSEB. Therefore, decreasing the porosity should cause an increase of thermal conductivity.

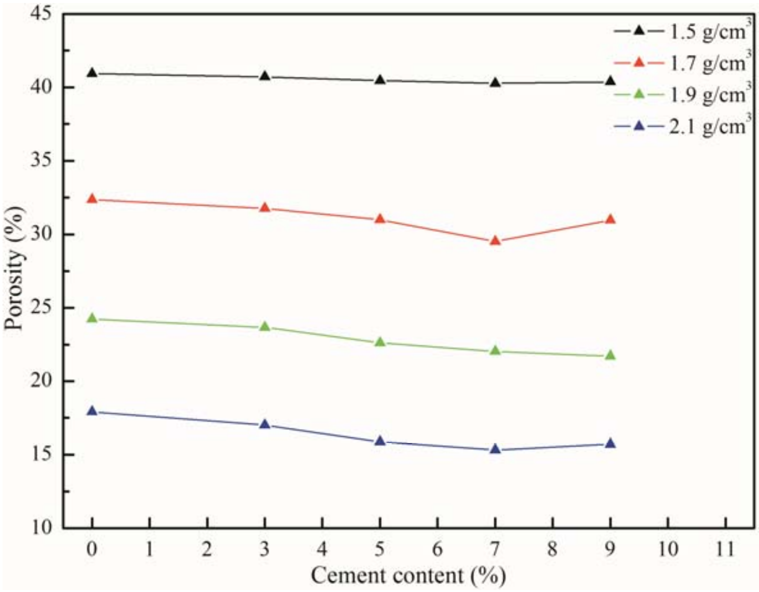

Fig. 9 Relationship between porosity and cement content for different bulk densities.

Ashour et al. [12] added cement into soil and tested the thermal conductivity of unfired earth bricks with cement. The results showed that the thermal conductivity slightly increased with increasing cement content. This phenomenon may be explained by hydration reaction of cement as polymerization for particles and filling for microstructure obtained from hydration products of cement. Fig. 10 shows the comparison of SEM images of unstabilized and cement stabilized earth blocks with 9 wt% cement at the same density content in our study. The two upper images show the differences of microstructure between unstabilized earth block and CSEB with 9 wt%, at a magnification of 500. There is no clear difference between the images and there is a similar compactness of the samples. The two lower images are enlarged versions of the designated areas as depicted in the red frames in the upper images. The results show that the isolated clay and quartz particles which originally existed in the unstabilized earth blocks have been embraced and then connected by the cementitious products (CSH and CAH), i.e. the cement has induced a homogeneous structure. This has also been shown by Reddy and Latha [32]. The hydration products formed during the cement hydration process slightly vary the compactness of the matrix, thus resulting in a small decreasing porosity of CSEB under the reinforcement of cemetitious products.

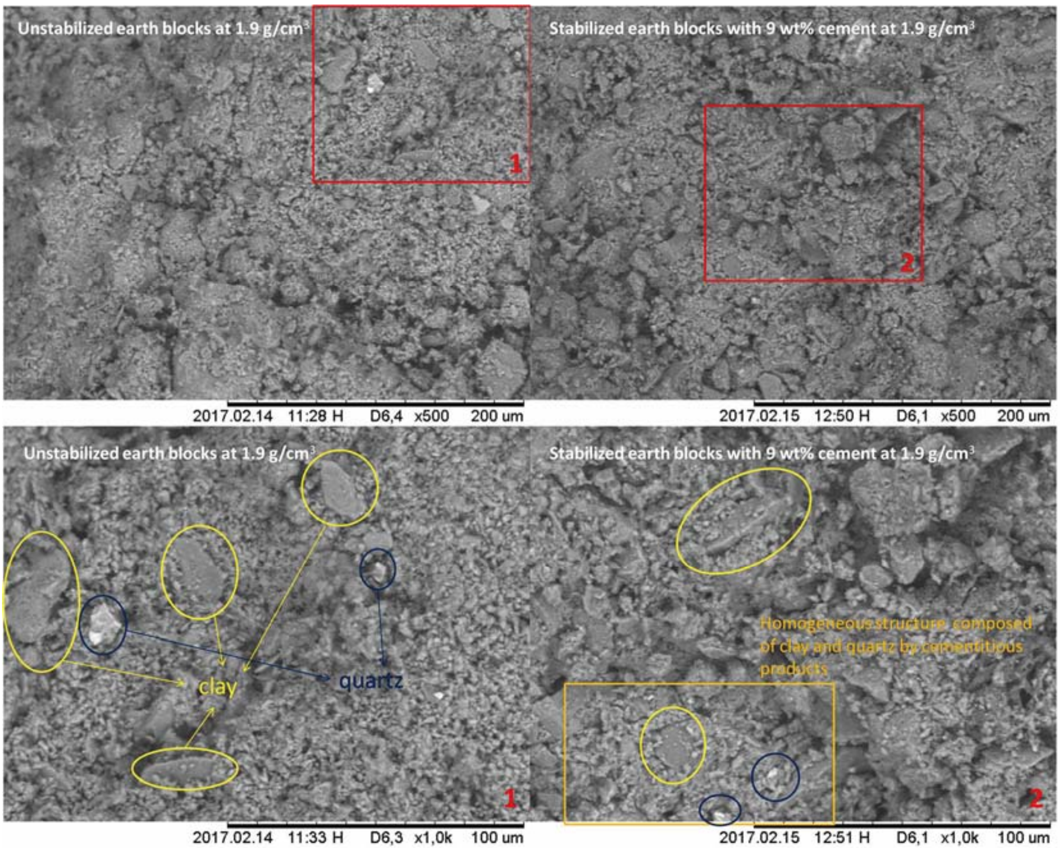

Fig. 10 SEM images of unstabilized and cement stabilized earth blocks.

Test values of thermal conductivity for both unstabilized and cement stabilized earth blocks at different bulk density values are shown in Fig. 11. The mean values of the thermal conductivity are presented with the uncertainty calculated as the standard deviation of the mean. The presence of cement causes a small variation of thermal conductivity, but no obvious trend between thermal conductivity and cement content was found.

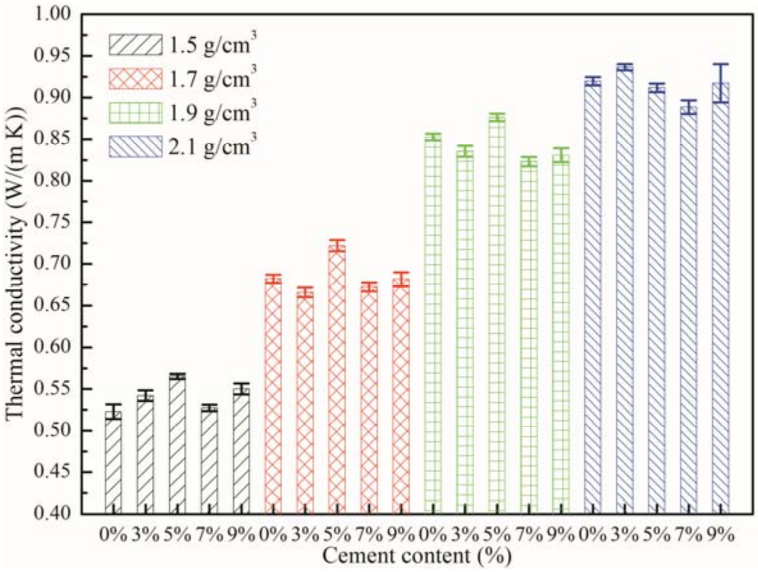

Fig. 11 Comparison of thermal conductivity for different cement contents and bulk densities.

Fig. 12 shows the relationship between thermal conductivity and cement content for different bulk densities. The mean values of thermal conductivity are presented with the uncertainty calculated as the standard deviation of the mean. Fig. 12 shows that there is not a strong relationship between thermal conductivity and cement content. At a given bulk density, the thermal conductivity with varying cement content varies within 5 % to 8 %, which is much less than the variation with bulk density.

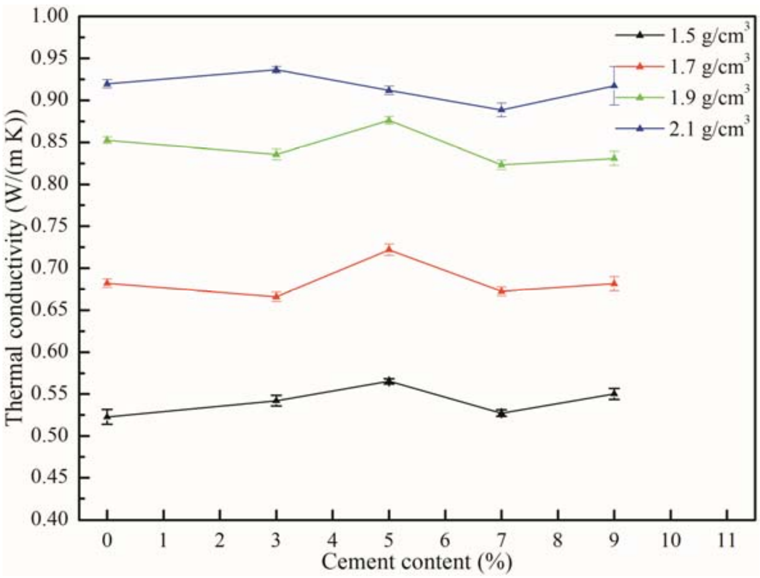

Fig. 12 Thermal conductivity vs. cement content for different bulk densities.

The above phenomenon may be explained by the variation of porosity with increasing cement content at different bulk density values. Fig. 12 shows that there is not an obvious thermal conductivity trend with cement content. The main reason may possibly be that the thermal conductivity of cement is similar to soil, i.e. Liu et al. investigated the thermal conductivity of cement paste with different modifiers and the results showed that the thermal conductivities changed from 0.72 W/(m K) to 1.02 W/(m K) [33]. Therefore, the thermal conductivity of CSEB does not obviously increase with a small addition of cement. In addition, the differences of cement content are so small that the hydration product amounts of cement are not large enough to vary the porosity value significantly. As shown in Fig. 9, there are very tiny differences between different cement content levels at a given bulk density. Also, the finite amount of cement causes that hydration products randomly distribute inside the CSEB matrix. Stochastic distribution led to a slight and random variation of thermal conductivity with cement content.

Unlike the thermal conductivity, there is a significant difference in the compressive strength of CSEB depending if cement or soil are used. Heathcote et al [7] analyzed the effect of cement on compressive strength of CSEB and results indicated that the compressive strength increases with increasing cement content. In our study, the compressive strength values are primarily corrected by the correction factor, and the influence of cement content on the corrected compressive strength, are shown in Fig. 13. The compressive strength of CSEB is significantly improved by cement and increases with increasing cement content. The main reason may be that the hydration products of cement have a high strength a magnitude higher than soil. Therefore, addition of cement is able to significantly increase the compressive strength of CSEB and only slightly vary the thermal conductivity. Earth buildings built by CSEB may possess the desired construction safety and thermal insulation properties in order to provide a comfortable indoor environment for residents.

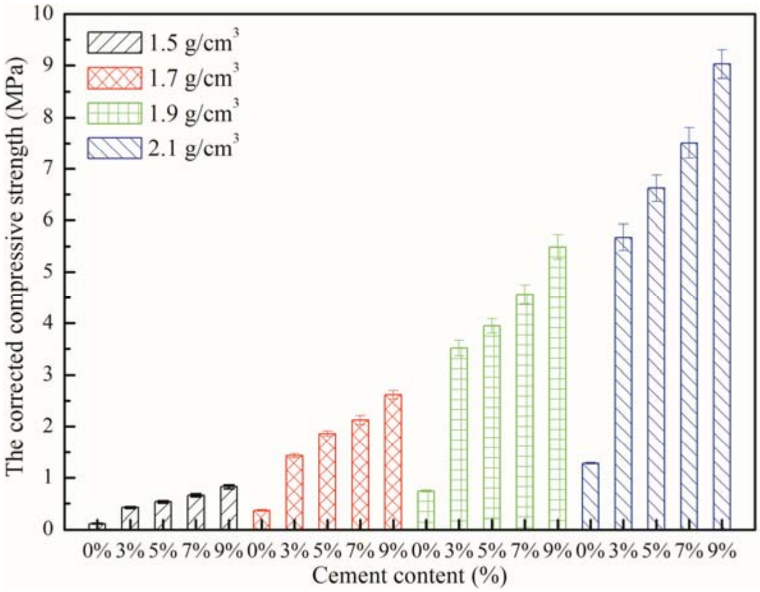

Fig. 13 Compressive strength vs. cement content for different bulk densities.

4. Conclusions

The aim of this study was to evaluate the effect of bulk density and cement content on the thermal conductivity of cement stabilized earth blocks (CSEB) and to guide the manufacturing of CSEB with a low thermal conductivity. Furthermore, the influence of different stabilizer types, stabilizer contents and mixed methods on the thermal conductivity of stabilized earth blocks should be investigated in further work. The following main conclusions can be drawn from this study:

1. The bulk density has a significant effect on the thermal conductivity values of CSEB. Increasing bulk density results in a reduction in porosity, thereby increasing the thermal conductivity values of CSEB. This can be explained by considering a two-phase composite consisting solid and air where air has a relative low thermal conductivity compared to soil and cement materials.

2. Addition of cement caused a small variation of the thermal conductivity, but no obvious trend between thermal conductivity and cement content was found. This might be due to that, the thermal conductivity of cement is similar to soil, and the dosage of cement in this study is probably not large

enough (< 9 wt%) to see a significant effect on the thermal conductivity.

3. The compressive strength of CSEB significantly increases with increasing cement. Its main reason may be that the hydration products of cement have a much higher strength than soil. Earth buildings built by CSEB may possess the desired construction safety and thermal insulation properties in order to provide a comfortable indoor environment for residents.

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