Simultaneous Investigation of Mechanical and Hygrothermal Properties of Lime Stabilized Earth Bricks

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Abstract. Lime stabilization has opposite effects on mechanical and hygric property of earth material. In order to determine the optimal lime content for earth material sourced from Turpan, the effects of lime content on both mechanical and hygrothermal properties of lime stabilized earth bricks (LSEB) are investigated simultaneously. The results indicate that there is an obvious correlation existed between the mechanical performance and lime content, and the max value of compressive strength and the minimum of loss of compressive strength after freezing-thawing cycles appear at lime content of 6 wt%. This phenomenon has been explained by effect of lime stabilization on the compactness inside LSEB matrix. When lime content is 6 wt%, thermal conductivity of LSEB is 0.9169 W/(m K) which is considered to be a tiny increase in comparison with LSEB without lime. In addition, all LSEB specimens are capable for regulating the indoor relative humidity.

Keywords: Compressive strength; freezing resistance; hygrothermal properties; lime stabilized earth bricks.

1. Introduction

With an acceleration of urbanization in China, a huge amount of building materials are required to be manufactured and used. The energy intensive materials (i.e. cement, concrete and steel) have high CO2 emissions and environmental impacts in their preparation and application, the sustainable replacement materials are being developed to satisfy the construction demands. Earth material is used to construct rural dwellings in China, and its abundant source results in preparation on-site and direct application and decreases further the economic costs and energy consumptions in acquisition, preparation and transportation. In addition, earth buildings are often considered to be available to regulate the indoor thermal, humid and acoustic environment. Nevertheless, the drawbacks of compressive strength, water resistance and durability restrict the application of earth material in modern construction sector. For the past few years, a series of studies were performed to improve the mechanical properties of earth material by using stabilization technique. Kukko [1] modified clay with binder alternatives and evaluated the stabilization effects on the mechanical properties of clayey soils. The results showed that lime stabilization has an obvious promotion effect and the strength of stabilized clay is depended on the lime content. To obtain a recommendable lime content, the unconfined compressive strength values of the stabilized rammed earth with different lime contents were examined in ambient conditions, and an optimum lime content of 4 wt% was identified to maximize the unconfined compressive strength [2]. Furthermore, water resistance, water sorptivity and shrinkage of lime stabilized earth brick (LSEB) were investigated, as well as weight loss after freezing-thawing cycle [3-5]. The results presented that LSEB exhibits better durability characteristics in comparison with unstabilized earth brick, as a cementitious
agent generated by reaction between clay minerals and lime connects the clay particles together and improves the compactness of matrix. It can be seen in previous studies that the improvement of mechanical properties of earth material by lime stabilization contrasts hygric performance. McGregor et al. [6] indicated that lime stabilization restricts the hygric properties of earth bricks in terms of equilibrium moisture content decreasing with lime content increases. In order to manufacture the earth brick having satisfactory physical properties, Millogo et al. [7] evaluated the impact of microstructural changes of LSEB on the mechanical resistance and water absorption. The experimental results presented that lime stabilization has a slight detrimental effect on the physical properties when lime content exceeds 10 wt%. In addition, the differences in both mineralogical and chemical composition of raw earth from various regions result in different effects of lime stabilization on the physical properties of earth material.

Turpan Prefecture is located in Northwest of China and has extremely cold winter with dry hot summer. Nowadays, local residents still live in the earth buildings for weather protection even though existing earth buildings have many problems with strength, durability and thermal performance. It is noteworthy that very few studies have been performed to improve the physical properties of earth material sourced from Turpan, in particular, the simultaneous analysis of mechanical and hygrothermal properties. In this study, LSEB specimens are prepared with different lime contents for physical properties characterization, i.e. compressive strength, loss of compressive strength after freezing-thawing cycles, thermal conductivity and equilibrium moisture content. The objective of this study is to investigate the mechanical and hygrothermal properties of LSEB, in order to guide the manufacture of LSEB for the purpose of reaching the requirements in the actual projects.

2. Experiments

2.1. Preparation of LSEB

2.1.1. Soil. In this study, the soil was collected from Turpan Prefecture, Northwest of China. The particle size analysis was performed to determine the grading curve and particle size of the soil, complying with GB/T 50123-1999 [8]. The experimental results present that the composition of the soil is 17 % clay, 51 % silt and 32% sand, as shown in Figure 1. In this study, the Atterberg limits test of the soil were conducted by using the Liquid-plastic Tester in accordance with JTJ 051-93 [9], and the liquid limit is 23.7 %, plastic limit is 18.2 % and plasticity index is 5.5 %. These results suggest that the soil is classified as silty clay and is appropriate to prepare earth bricks for the construction sector. The mineralogical composition of the soil was estimated by using X-ray diffraction analysis and the results indicated that the soil used in this study includes quartz (SiO₂), calcite (CaCO₃), anorthite (CaAl₂Si₂O₈) and albite (NaAlSi₃O₈) minerals, as demonstrated in Figure 2.

![Figure 1. Particle size curve of soil in this study.](image1.png)

![Figure 2. Mineralogical composition of soil in this study.](image2.png)
2.1.2. 

**Hydrated Lime.** Because the hydrated lime has been characterized to improve the compressive strength of compressed earth bricks, it was used to modify the earth material in this study. The hydrated lime complied with HCL 85 JC/T 481-2013 [10]. The purity and fineness values were 90 % and 45 μm, respectively.

2.1.3. 

**Lime stabilized earth bricks (LSEB).** Prior to preparation of LSEB, the soil was sieved towards removing oversized granules (more than 2 mm diameter) and all impurities, and then the sieved soil was placed in an oven at 105 °C until the constant weight was achieved. The oven-dried soil was mixed with hydrated lime at different mass ratio between soil and lime (96:4, 94:6, 92:8, 90:10). Water was added into the mixture at a W/M ratio of 13 % (W is mass of water, and M is mass of mixture) which was determined by using standard Proctor compaction test, according to GB/T 50123-1999 [8]. The mixture containing water was mixed to be uniform by wetness and this process usually takes about 10 min. The wet mixture was put into the steel mould and then was compacted at a bulk density of 2.0 g/cm³ by using a hydraulic press. It is noteworthy that the bulk density could be determined by mass of specimen divided by its volume. In this study, two sets of specimens were selected to characterize the mechanical and hygrothermal properties of LSEB, respectively. Ten specimens with dimensions of 50 mm × 50 mm × 50 mm were prepared for investigating both compressive strength and loss of compressive strength after freezing-thawing cycles, while ten specimens with dimensions of 50 mm × 50 mm × 25 mm were prepared for hygrothermal properties tests. When compaction of LSEB specimen was completed, the specimens were demould and then were placed in controlled environment at air temperature of 20 ± 1 °C and relative humidity of 60 ± 1 % RH for 28 days in order to assure the lime hydration.

2.2. 

**Characterization**

2.2.1. 

**Compressive strength.** At the current stage, different dimensions and shapes of specimen were selected to characterize compressive strength. In this study, a cubic specimen with a length of 50 mm on each side was selected to determine the compressive strength of LSEB and the compressive strength values of oven-dried LSEB specimens were characterized by using a hydraulic press in accordance with GB/T 50081-2002 [11]. The compressive strength test of LSEB with each lime content was repeated three times and the average value was reported.

Ozkan et al. [12] indicated that the lateral deformation of the specimen caused by compression force is confined by friction between the specimen and the platens, results in an obvious increasing compressive strength value. Considering the impacts of platen restraint, the compressive strength values were corrected by using a height to thickness correction factor. In this study, the correction factor was confirmed as 0.70 according to the height/thickness ratio of specimens.

2.2.2. 

**Loss of compressive strength after freezing-thawing cycles.** In this study, LSEB specimens were exposed to 50 freezing-thawing cycles in order to measure the compressive strength of LSEB after freezing-thawing cycles. Before the freezing-thawing tests, the 28 day-cured specimens were placed in a container at a relative humidity of 97 %RH for 24 h, towards reaching a saturation. The saturated specimens were placed in a freezer at a constant temperature of -20 °C for 24 h and then removed to a controlled chamber at a constant temperature of 20 °C for 24 h. 24 h was selected to ensure the specimens were frozen and thawed completely. The 24 h freezing process followed by the 24 h thawing process was deem to be a single freezing-thawing cycle and the freezing-thawing cycle was repeated 50 times. The specimens subjected to 50 freezing-thawing cycles were measured to characterize the compressive strength of LSEB after freezing-thawing cycles, according to GB/T 50081-2002 [11]. The loss of compressive strength after freezing-thawing cycles was then calculated by using the following equation:

\[
\mu = \frac{f_0 - f_{50}}{f_0} \times 100\%
\]

Where \(f_0\) is the compressive strength of oven-dried LSEB [MPa], \(f_{50}\) is the compressive strength of LSEB after 50 freezing-thawing cycles [MPa].
2.2.3. Thermal conductivity. In this study, Hot Disk apparatus was used to examine thermal conductivity values of LSEB specimens. Before the measurement, the surfaces of specimens were polished to obtain an ideal contact between the testing sensor and the surfaces of specimen. After the pre-processing, the polished specimens were stored in an oven at 105 °C until the constant mass was achieved. Thermal conductivity measurement of each oven-dried LSEB specimen was repeated three times and the average value was reported.

2.2.4. Adsorption-desorption isotherms. In order to describe the hygroscopic property of LSEB, adsorption-desorption isotherms were used in this study. Adsorption-desorption isotherms was consisted of an adsorption branch and a desorption branch. The adsorption branch presents the measured specimen absorbs water vapour in a range of relative humidity, and then the desorption branch indicates that the adsorbed vapour is released from the specimen matrix when the relative humidity reduces. In this work, the adsorption-desorption isotherms measurements of LSEB specimens were carried out by using the saturated salt solutions method [13]. Prior to measurements, all LSEB specimens were placed in an oven at 105 °C until constant mass was achieved. As shown in Table 1, different relative humidity environments were established by six saturated salt solutions for performing absorption-desorption isotherms tests. The oven dried LSEB specimens were placed successively in sealed desiccators with relative humidity increases. The sealed desiccators were stored in a controlled environment (60 % RH and 20 °C), and then the measured specimens were daily weighed until constant mass of each specimen was achieved. When the measured specimens reached a hygroscopic equilibrium in the last testing surrounding (97.3 ± 0.3 % RH), the adsorption procedure experiments were finished and then the reverse process was performed in order to measure the desorption procedure. The desorption procedure experiments were finished when the measured specimens achieved a constant mass at 32.8 ± 0.2 % RH condition.

| Molecular formula | MgCl₂ | K₂CO₃ | Mg(NO₃)₂ | CoCl₂ | KCl | K₂SO₄ |
|-------------------|-------|-------|----------|-------|-----|-------|
| Relative humidity (%RH) | 32.78±0.2 | 43.16±0.1 | 52.89±0.2 | 64.92±0.2 | 84.34±0.1 | 97.30±0.3 |

3. Results and Discussion

3.1. Compressive Strength
In order to eliminate the effect of platen restraint, the compressive strength values of LSEB were corrected by the height/thickness correction factor in this study. It can be seen in Figure 3, the corrected compressive strength values of LSEB are expressed by average values with the uncertainty which is calculated as the standard deviation of the average. What is noteworthy is that the lime stabilization has an obvious effect on the compressive strength of earth material. In detail, the compressive strength of earth brick without lime is 1.06 MPa, which is considered to be below the required value of 2.00 MPa and to be insufficient for the construction safety. When earth brick is stabilized with lime, the compressive strength of LSEB increases significantly. Especially, the maximum of compressive strength is appeared when lime content increases up to around 6 wt%. Compared with earth brick without lime, the compressive strength of LSEB with 6 wt% lime is 1.80 MPa higher. A similar trend can be found in a previous study [14], where the lateritic soil was stabilized by using lime and the maximum compressive strength of lime stabilized soil was 0.749 MPa at a certain lime content of 4 wt%. This result can be explained by the increasing cohesion of the earth matrix caused by addition of lime.

3.2. Loss of Compressive Strength after Freezing-thawing Cycles
Figure 4 presents the compressive strength and loss of compressive strength after freezing-thawing cycles. For the LSEB specimen without lime (i.e. lime content = 0 wt%), the compressive strength after freezing-thawing cycles is 0.51 MPa and the loss of compressive strength is as high as 51.89 %. This result shows that the walls built with earth brick without lime will loss their bearing capacity under freezing-thawing cycles with the season progresses. Compared with earth brick without lime, the
compressive strength loss of LSEB reduces significantly. This phenomenon may also be explained by the effect of lime stabilization. When lime content increases up to 6 wt%, the maximum compressive strength after freezing-thawing cycles and the minimum loss of compressive strength appear simultaneously. With lime content further increases, the loss of compressive strength after freezing-thawing cycles increases obviously. It is noteworthy that when lime content is 6 and 8 wt%, the loss of compressive strength of LSEB is 16.08 and 23.91%, respectively. These results are considered to be lower than the required value of 25% according to GB 50574-2010 [15].

![Figure 3. Relationship between lime content and compressive strength of LSEB.](image1)

![Figure 4. Compressive strength loss of LSEB subjected to freezing-thawing cycles.](image2)

### 3.3. Thermal Conductivity

The evolution of thermal conductivity average value for LSEB with lime content has been presented in Figure 5. Thermal conductivity of LSEB increases as lime content increases from 4 to 6 wt%, and then decreases when lime content exceeds 6 wt%. In order to explain the effect of lime content on thermal conductivity of LSEB, the porosity measurements have been performed by using Le Chatelier Flask. A correlation existing between the bulk density and porosity can be also found in Fig. 10. When lime content increases from 4 to 6 wt%, the porosity of LSEB decreases significantly, and less air exists inside the matrix because oven-dried LSEB specimen can be deemed as a composite comprised of solid phase (earth and lime) and air phase. Compared with solid phase, air has a very low thermal conductivity of about 0.026 W/(m K). Consequently, decreasing the porosity leads to an increase in thermal conductivity of LSEB with lime content increases from 4 to 6 wt%. When lime content further increases, excessive lime enhances the pH value inside LSEB matrix and then dissolves the soil particles in order to increase the porosity of LSEB. Therefore, thermal conductivity of LSEB decreases significantly when lime content increases from 6 to 10 wt%.

![Figure 5. Thermal conductivity and porosity vs. lime content of LSEB.](image3)

According to the results in Chapter 3.1 and 3.2, the satisfactory compressive strength and loss of compressive strength after freezing-thawing cycles can be observed when lime content of LSEB is 6
and 8 wt%. It is noteworthy that the average value of thermal conductivity for LSEB with 6 wt% lime is 0.9169 W/(m K) which is considered to be a tiny increase in comparison with LSEB without lime (i.e. lime content = 0 wt%). This phenomenon suggests that as a crucial parameter for evaluating thermal insulation of building wall, the average thermal resistance of LSEB wall will decrease slightly when 6 wt% lime is used for stabilization.

3.4. Adsorption-desorption Isotherms

The development of moisture content of LSEB subjected to developing relative humidity is characterized by using saturated salt solutions method in this study. The evolutions of moisture content with time for LSEB specimens show that the equilibrium moisture content values of tested specimens almost reach a constant value in four days, as shown in Figure 6. This phenomenon demonstrates that when relative humidity changes, LSEB specimens are capable for quickly absorbing water vapour from environment towards regulating the indoor relative humidity. In addition, it is expressive to observe a visible correlation between the equilibrium moisture content of LSEB and lime content. The equilibrium moisture content of LSEB increases with lime content increases from 4 to 6 wt% and then reduces with lime content further increases.

![Figure 6. Development of moisture content of LSEB with relative humidity increases.](image)

![Figure 7. Adsorption-desorption isotherms of LSEB with different lime contents.](image)

The adsorption-desorption isotherm curves for LSEB specimens are illuminated in Figure 7. As shown in this figure, the adsorption-desorption isotherms of all LSEB specimens have the similar profiles that there are two inflections on the adsorption isotherm curve. In detail, the inflection located between the 50 %RH and 55 %RH indicates that there is a strong increase in equilibrium moisture content when relative humidity is low and the single layer surface adsorption occurs. When ambient relative humidity increases further, the multilayer surface adsorption replaces the previous adsorption mechanism towards describing a weaker absorbency for water vapour. In addition, when the relative humidity increases to a high level, the equilibrium moisture content significantly increases again because the capillary condensation occurs in this zone of the adsorption curve. A distinct variation between adsorption and desorption curves defined as hysteresis can be also checked in Figure 7. According to McGregor et al.’s study [6], hysteresis is correlative with capillary condensation and can be used as a credible parameter to determine the moisture buffering. When the tested specimens have finished the adsorption curve measurement, they are removed into a lower relative humidity environment to release water vapour. The adsorbed water molecules can not be immediately released into environment as the narrow pores inside matrix are blocked with condensed water.

4. Conclusions

In this study, a series of experimental researches were conducted to determine the mechanical and hygrothermal properties of lime stabilized earth bricks (LSEB). The effect of lime content on the compressive strength, loss of compressive strength after freezing-thawing cycles, thermal conductivity and equilibrium moisture content of LSEB were summarized as following:
The compressive strength of LSEB increased with lime content increases from 4 to 6 wt%, and then decreased when lime content exceeded 6 wt%.

Lime stabilization is capable for reducing loss of compressive strength of LSEB after freezing-thawing cycles and the minimum of loss of compressive strength could be obtained when lime content of LSEB was 6 wt%. When 6 or 8 wt% lime were used in the preparation of LSEB, the mechanical properties (i.e. compressive strength and loss of compressive strength after freezing-thawing cycles) were deemed to satisfy the required value according to relevant standards.

Compared with LSEB without lime, thermal conductivity of LSEB with different lime contents expressed a slight variation. In especial, thermal conductivity of LSEB with 6 wt% lime is 0.9169 W/(m K) which is considered to be a tiny increase in comparison with LSEB without lime.

All LSEB specimens were capable for regulating the indoor relative humidity, and LSEB with 6 wt% lime had the best adsorption capacity in this study.

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