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Mechanical and Thermal Conductivity Study of Inorganic Modified Raw Soil Materials Based on Gradient Concept

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Abstract: Based on the inorganic modification of raw soil materials by using cement, fly ash, lime and other admixtures, the influence of modified jute fiber content on the strength of raw-soil-based wall materials was studied. The effects of the gradient distribution of inorganic admixtures on the mechanical properties and thermal conductivity of raw-soil-based wall materials were studied and compared by designing the gradient distribution and homogenous distribution of admixtures in raw soil materials. The results show that when the mass ratio of raw soil, sand, cement, fly ash and lime is 30:10:5:3:2, the compressive strength and flexural strength of the modified raw soil specimen at 28 d are 6.4 MPa and 2.9 MPa, respectively; on the basis of the further addition of 0.8 v% jute fibers, the strength can still be enhanced by 20% and its thermal insulation properties will also be improved. Gradient design can further improve the mechanical properties of modified raw-soil-based wall materials and can weaken the loss of its inherent thermal insulation function.

Keywords: raw soil materials; gradient distribution; mechanical properties; thermal conductivity

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1. Introduction

Raw soil is the most traditional building material used by humankind. In modern society, trending toward urbanization, about 30% of the population lives in raw soil buildings [1,2]. Due to its excellent properties such as low carbon environmental protection, convenient materials, heat preservation and humidity control [3], and it can return to nature after service and still continue to grow crops, so it is favored by many scholars. However, the mechanical properties and water resistance of traditional raw soil materials are poor, which limits their development. How to improve their properties while ensuring the advantages of raw soil materials is the key to further popularization and application [4].

At present, the modification research on raw soil materials has been carried out in an orderly manner. Jayasinghe found that the compressive strength of modified raw-soil-based wall materials improved significantly when the cement content was greater than 6 wt% [5]. The research results from Yang Yong [6] showed that the mechanical properties of raw-soil-based wall materials reached an extreme value when the cement content was 15 wt%, but the thermal insulation properties were reduced. Ciancio et al. [7] studied the effect of lime on the modification of raw soils and found that the optimum content of lime was 4 wt%, under which the compressive strength of raw soil reached the maximum at 28 d. Beyond this value, no additional beneficial changes in strength were observed. Based on the volcanic ash effect and dispersion effect of fly ash, Ma [8] studied the effect of fly ash on the compressive strength of raw soil materials. Burroughs [9] analyzed 104 kinds of soil and modified the soil with lime and cement. The results showed that only when the unconfined compressive strength of the soil itself was greater than 2 MPa could a good consolidation strengthening effect be achieved. Liu Jun et al. [10] studied the effect of single and compound doping of fly ash, cement and other admixtures on the mechanical properties of raw-soil-based wall materials; the results showed that

when the single admixture was added, the cement had a better modification effect on the mechanical properties of the raw-soil-based wall materials. Compared with the single material modification, the compressive strength and flexural strength of the composite-modified raw-soil-based wall materials were increased.

Achievements have also been made in the study of plant fibers for soil modification. Agricultural waste fibers were used to modify the soil. When the fiber content was 0.5 v%, the compressive strength and durability of the soil block were significantly enhanced [11]. Yetgin et al. [12] found that straw fibers could improve the mechanical properties of the mud and that the compressive and tensile strengths of the soil blanks increased and the shrinkage decreased with the increase in fiber content. Liu Junxia et al. [13] pointed out that the original jute fiber had no obvious effect on the improvement of the flexural strength of raw-soil-based wall materials, while the modified jute fiber could improve the mechanical properties of raw-soil-based wall materials.

The aforementioned research is mainly to improve the properties of the raw soil by modifying the material and has not considered the existence of a large number of interface weak areas between the internal heterogeneous phases of the modified raw soil materials [14]. The weak interface zone refers to the large difference in elastic modulus and thermal expansion coefficient between the phases, which is prone to stress concentration. If the interface weak areas can be diminished through modern technology and means, the properties of the modified raw-soil-based wall material can be further improved. Functionally gradient materials are a new type of non-homogeneous composite material with continuous and stable changes in performance by selecting two or more materials with different properties according to the actual requirements and using advanced composite technology to make the components and structure change in a continuous gradient [15]. Compared with traditional homogeneous materials, the material content changes in a gradient, so its properties are in a gradual form, which can avoid or alleviate the stress concentration caused by the excessive difference in physical properties of the component interface, so as to avoid cracking or spalling defects [16].

The research on functionally gradient materials mainly focuses on the fields of metals, ceramics and composite materials [17,18], and research on gradient modification of raw soil is relatively rare. Therefore, it is considered to apply the gradient concept to the modified raw-soil-based wall materials, so as to improve the mechanical properties of the modified raw-soil-based wall materials, reduce the loss of its inherent thermal insulation function, and realize the integration of structural functions. In this paper, the influence of modified jute fiber content on the properties of raw-soil-based wall materials was studied on the basis of inorganic materials modified with raw soil. Through the gradient distribution and homogenous distribution of inorganic admixtures in raw-soil-based wall materials, the influence of gradient design on the mechanical properties and thermal conductivity of raw-soil-based wall materials was studied.

2. Materials and Methods

2.1. Raw Materials

The chemical composition of raw soil, cement (P.O 42.5) and fly ash is shown in Table 1. The raw soil was taken from a region of the Loess Plateau in northern Shaanxi. The total content of five main components, SiO_2, Al_2O_3, Fe_2O_3, CaO and MgO, accounts for more than 80%. The raw soil below 0.15 mm in size was screened and dried at 105 °C for use. The test sand was ISO standard sand produced in Xiamen, the total content of SiO_2 was more than 96 wt%, and the loss on ignition was less than 0.4 wt%. Ordinary Portland cement (P.O 42.5) was produced by Tianrui Group Cement Co. Ltd. (Zhengzhou, China). Fly ash was provided by Kaifeng power plant and the specific surface area and activity index of the fly ash were 463 m^2/kg and 0.97, respectively. The lime was the hydrated lime produced by Songshan Lime Factory (Dengfeng, China). The effective component of $Ca(OH)_2$ was not less than 70%, and the particle size was less than 0.15 mm. The water-reducing agent was AJ-2Z retarding aliphatic water-reducing agent produced by Zhongtie Concrete Admixture

Factory (Anhui, China). The length of jute fibers was about 8 mm, the length/diameter ratio was 70, and the density was 1.1 g/cm^3.

Table 1. Chemical composition of raw soil, cement and fly ash.

Composition	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	Others
Raw soil (wt%)	1.99	64.47	2.29	12.08	1.41	--
Cement (wt%)	58.86	19.27	3.36	5.10	2.61	4.06
Fly ash (wt%)	4.01	55.07	4.59	27.05	1.52	3.85

2.2. Experimental Design and Sample Preparation

2.2.1. Modification of Inorganic Materials

Raw soil was used as raw material and the raw-soil-based wall material was modified by adding cement, fly ash, lime and other admixtures, as shown in Table 2. After the raw soil and lime were aged for 24 h, standard sand, cement and admixture were added and fully stirred in the mixer for 2 min, followed by mixing water and water reducer for 2 min, and finally stirred at high speed for another 1 min. The modified raw-soil-based wall material was poured into a triple mold with a size of 40 mm × 40 mm × 160 mm for vibration molding. After 1 d, the mold was removed and the test block was placed under natural conditions (temperature of 20 ± 5 °C, humidity of about 50%) for curing. According to the "Cementitious Sand Strength Test Methods (ISO method)" (GB/T 17671-2021) [19] the compressive strength and flexural strength of the specimen at 7 d and 28 d were measured. The compressive strength and flexural strength were carried out on the DY-208JX automatic pressure testing machine, wherein the loading speed of the compressive strength was 1 kN/s and the loading speed of the flexural strength was 50 N/s.

Table 2. Mix proportion design of inorganic modified materials (wt%).

Number	Raw Soil	Sand	Cement	Fly Ash	Lime	Water/Solid Ratio	Water-Reducing Agent
A_0	80	20				0.24	0.1
A_1	60	20	4	8	8	0.24	0.1
A_2	60	20	5	8	7	0.24	0.1
A_3	60	20	6	8	6	0.24	0.1
A_4	60	20	6.4	6.6	6.6	0.24	0.1
A_5	60	20	8	6	6	0.24	0.1
A_6	60	20	8	8	4	0.24	0.1
A_7	60	20	10	6	4	0.24	0.1
A_8	60	20	10	5	5	0.24	0.1
A_9	60	20	12	4	4	0.24	0.1
A_{10}	60	20	12	5	3	0.24	0.1
A_{11}	60	20	13	4	3	0.24	0.1
A_{12}	60	20	14	3	3	0.24	0.1

2.2.2. Plant Fiber Modification

On the basis that the mechanical properties of raw-soil-based wall materials modified by inorganic admixtures meet the requirements, the influence of plant fiber on its performance was explored. Jute was immersed in 5 wt% NaOH solution for about 12 h, and then the residual NaOH solution on the surface was washed with water. The oily substance on the surface of jute fiber could be removed by a strong alkali solution, which made the grooves on the surface of jute clearer and increased the roughness of the surface of the jute [13]. The specimen preparation process is the same as that of inorganic material modification, except that jute fiber is added. After stirring the inorganic modified material and water-reducing agent in the mortar mixer for 2 min, the modified jute is fully dispersed in the standard weighing water, and the mortar mixer is added to continue to stir at low speed for 2 min and then stirred at high speed for 1 min. The volume content of jute fiber varies from 0 to 1.6 v% with a ratio of 0.2 v%.

2.2.3. Gradient Design

When the number of gradient layers is 4, the thermal stress and stress concentration area between the gradient layers are minimized, and the internal tensile stress of the material reaches the minimum value [20]. Using four layers of functionally graded fiber-reinforced cement-based composites, the strength and fracture function of the gradient specimen designed by the gradient design are increased by about 50% compared with the homogenous specimen [21]. Based on the determination of inorganic admixture and modified jute fiber content, the gradient design test was carried out, in which the gradient layer was designed to be 4 layers and the size of each layer was equally divided, as shown in Figure 1.

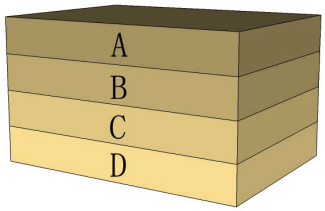


Figure 1. Gradient model.

The size of the gradient specimen and the homogenous specimen used for mechanical properties testing were both 40 mm × 40 mm × 160 mm and the size of each layer of the gradient sample was 10 mm × 40 mm × 160 mm, so the preparation method and process were similar to those of the homogenous specimen. However, in the preparation process of the gradient specimen, each gradient layer needs to be separately proportioned and stratified. After forming the gradient specimen, it was cured under indoor natural conditions for 24 h before the mold was removed, and then the specimen block was placed under the indoor natural conditions for water spray curing; the curing temperature was 20 ± 5 °C and the relative humidity was about 50%. The direction of force on the modified raw soil base gradient specimen were kept perpendicular to the direction of the gradient during the compressive strength test. The size of the specimen for the thermal conductivity test was 250 mm × 250 mm × 25 mm, the size of each layer was 250 mm × 250 mm × 6.25 mm, and the specimen was demolded 1 d later and placed under the indoor natural conditions for water spray curing; the curing temperature was 20 ± 5 °C, and the relative humidity was about 50%. The surface of the specimen was polished and dried to constant weight in a drying oven with a set temperature of 105 °C. According to the standard "Determination of steady-state thermal resistance and related characteristics of thermal insulation materials-Protection hot plate method" (GB/T 10294-2008) [22] the dried specimen was fixed on the DRM-1 type thermal conductivity tester for testing, and the measurement time lasted 24 h.

3. Results and Discussion

3.1. Inorganic Admixture Modified Raw Soil Strength

Figure 2 shows the strength development pattern of modified raw-soil-based wall materials with the content of inorganic admixture changing continuously. Combined with the analysis of Figure 2 and Table 2, it can be seen that the strength of modified raw-soil-based wall materials shows an increasing trend with the increase in the proportion of cement in the admixture, and the effect of modified materials on its compressive strength was obviously better than that of the flexural strength. This is similar to the results of Kim, who noted that the unconfined compressive strength of raw soil increases with the increase in cement content [23]. From the strength changes of A_5 to A_6 and A_7 to A_8, it can be seen that under a certain amount of cement, the compressive and flexural strength can be further improved by appropriately increasing the content of fly ash and decreasing the content of lime; in particular, the strength change over 28 d is more obvious. From the strength changes of A_9 to A_{10}, it can be seen that when the cement content is further increased, the effect of the change in the content of fly ash and lime on the strength of

the modified raw-soil-based wall materials will be weakened. When the mixing ratio of cement, fly ash and lime is 14:3:3, the compressive strength and flexural strength of 7 d reached 3.8 MPa and 1.4 MPa, respectively, which were 6.6 times and 6 times higher than those of the raw soil specimen without inorganic modified materials. When the age reached 28 d, its compressive and flexural strengths reached 7.1 MPa and 3.1 MPa, which were 1.9 times and 2.1 times higher than those of 7 d, indicating that the strength of the modified raw-soil-based wall materials improved with the increase in the length of the curing period. This is because fine cement and fly ash particles fill in the voids of raw soil particles, reducing the number of voids. With the increase in age, the cement further reacts fully and generates more hydraulic gelling products, which enhances the cohesion between the loose raw soil particles and thus improves the strength of the specimen [10]. At the same time, fly ash will also react with $Ca(OH)_2$ to form gel, which will closely link the soil and further improve the strength of the modified raw-soil-based wall material. The compound additions of several admixtures can complement each other and effectively avoid the damage or fracture of raw-soil-based wall materials caused by internal structural defects [24].

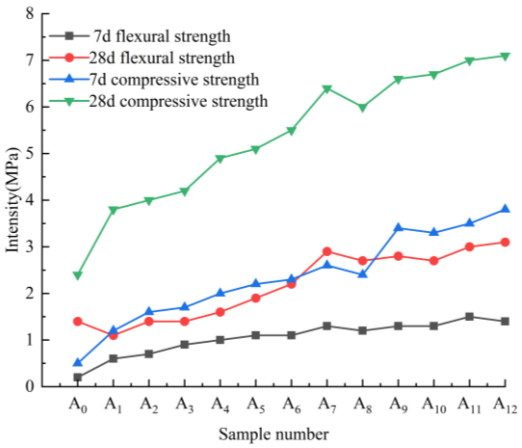


Figure 2. Effect of inorganic material mix ratio on mechanical properties of raw soil materials.

Considering the availability of raw soil buildings after returning to nature, adding too much admixture makes the soil more alkaline, which is not conducive to the growth of crops. Meanwhile, with the further increase in cement content, the strength growth rate of modified raw soil specimen is slow, so the A_7 group is the best ratio of this group of tests, and its 28 d compressive strength and flexural strength reach 6.4 MPa and 2.9 MPa, respectively. Among them, 60% was raw soil, 20% was standard sand, 10% was cement, 6% was fly ash and 4% was hydrated lime; that is, the mixing ratio of cement, fly ash and hydrated lime was 5:3:2.

3.2. Strength of Plant Fiber Modified Raw Soil

Figure 3 shows the influence of modified jute fiber content on the mechanical properties of modified raw-soil-based wall materials. Under the condition that the mechanical properties meet the requirements, the influence of jute on the mechanical properties of inorganic modified raw soil-based wall materials is further discussed. The proportion of admixture in the modified raw-soil-based wall material was 20 wt%; the proportion of cement, fly ash and lime was 10 wt%, 6 wt% and 4 wt%, respectively. It can be seen from Figure 3 that when the jute content was 0.8 v%, the compressive and flexural strengths of the modified raw soil specimen were 7.8 MPa and 3.6 MPa, respectively, which were 22% and 24% higher than those of the raw soil materials without modified jute fiber. This is because the surface of the modified jute fiber is rougher and has a higher degree of bonding with the raw-soil-based material. Under the action of external force, due to the strong bonding force between fiber and soil-based materials, fiber will consume some of

the energy in the process of pulling out, delaying the development of cracks, so the strength of soil-based material can be improved, which is similar to the net root system of the plant to fix the soil. In addition, when the content of jute fiber is less than 0.8 v%, the strength of the modified raw-soil-based wall material increases with the increase in the fiber content, but when the content exceeds 0.8 v%, the compressive strength and flexural strength have a downward trend. Considered comprehensively, 0.8 v% is set as the optimum content of modified jute.

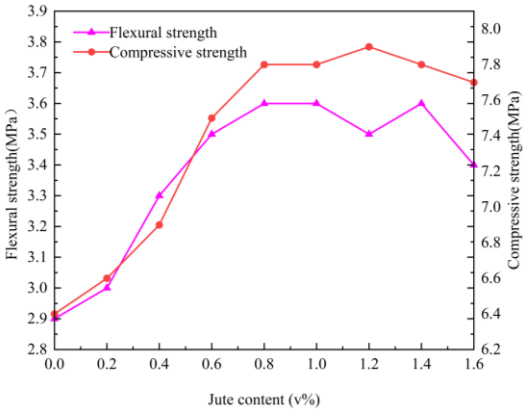


Figure 3. Relationship between strength and jute content.

3.3. Mechanical Properties and Thermal Conductivity of Modified Raw-Soil-Based Gradient Specimens

In order to carry out the gradient design, on the basis of the above-mentioned admixture modified raw soil, the proportion of cement, fly ash and hydrated lime was controlled to be constant (5:3:2), while the total admixture shows a gradient change to determine the proportion of the admixture in each gradient layer. The content of modified jute in each gradient layer was 0.8 v%.

Figure 4 shows the change rule of mechanical properties of the modified soil-based wall material when the standard sand content was 20 wt%, the modified jute was 0.8 v%, and the total content of cement, fly ash and hydrated lime (the incorporation ratio is 5:3:2) was constantly changing. The results show that when the total amount of inorganic admixture varies from 12 wt% to 22 wt%, the compressive strength and flexural strength of the modified raw-soil-based wall materials were positively correlated with the amount of admixture. The minimum compressive strength and flexural strength of 28 d were 4.4 MPa and 2.5 MPa, respectively, which meet the requirements of mechanical properties of wall materials. The 7 d compressive strength of the modified raw-soil-based wall material reached 3.6 MPa when the proportion of the admixture was 22 wt%, which was 1.1 times higher than that of the unmodified raw soil, and the 28 d compressive strength reached 8.3 MPa. The flexural strength of 7 d and 28 d reached 2.2 MPa and 3.9 MPa, respectively, which was 2.7 times and 1.3 times higher than that of raw-soil-based materials without inorganic modified materials.

Based on the above results, the preparation of the gradient specimen was carried out on the basis of determining the mixing ratio of each gradient layer admixture. Table 3 shows the mixture ratio design of gradient distribution and homogenous distribution of inorganic modified admixtures in raw soil materials, where M represents the gradient distribution of inorganic modified admixture and N represents the homogenous distribution of inorganic modified admixture. Measures of 0.15 N, 0.17 N and 0.19 N represent the homogenous distributed specimens with 15%, 17% and 19% inorganic modified admixtures, respectively; 0.15 M, 0.17 M and 0.19 M represent the gradient distribution specimens with inorganic modified material content of 15%, 17% and 19%, respectively; 0.19 N, 0.17 N and 0.15 N were controls of 0.19 M, 0.17 M and 0.15 M, respectively.

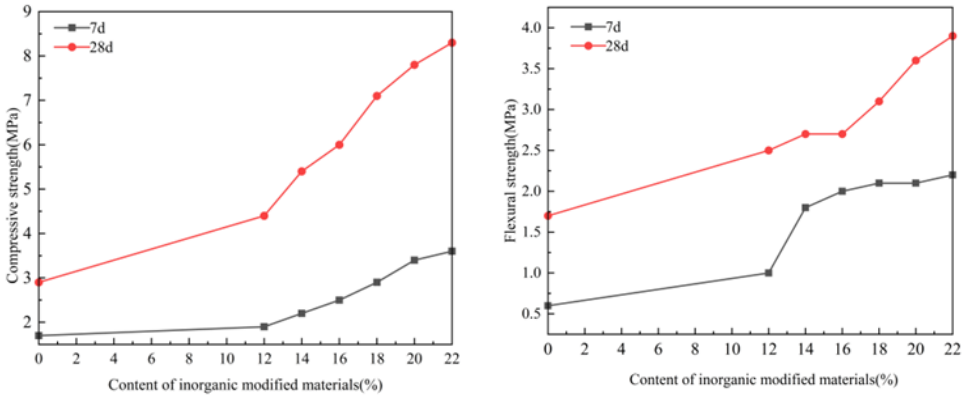


Figure 4. Effect curve of inorganic modified material (cement, fly ash and lime) content on mechanical properties of raw-soil-based material. (**a**) Compressive strength. (**b**) Flexural strength.

Table 3. Mix ratio design of gradient specimens and homogenous specimens.

Sample		Raw Soil (wt%)	Sand (wt%)	Inorganic Modified Materials (wt%)	Jute (V%)	Water-Reducing Agent	Water-Solid Ratio
0.19 M	Layer 1	58	20	22	0.8	0.1	0.24
	Layer 2	60	20	20	0.8	0.1	0.24
	Layer 3	62	20	18	0.8	0.1	0.24
	Layer 4	64	20	16	0.8	0.1	0.24
0.19 N	Control	61	20	19	0.8	0.1	0.24
0.17 M	Layer 1	60	20	20	0.8	0.1	0.24
	Layer 2	62	20	18	0.8	0.1	0.24
	Layer 3	64	20	16	0.8	0.1	0.24
	Layer 4	66	20	14	0.8	0.1	0.24
0.17 N	Control	63	20	17	0.8	0.1	0.24
0.15 M	Layer 1	62	20	18	0.8	0.1	0.24
	Layer 2	64	20	16	0.8	0.1	0.24
	Layer 3	66	20	14	0.8	0.1	0.24
	Layer 4	68	20	12	0.8	0.1	0.24
0.15 N	Control	65	20	15	0.8	0.1	0.24

3.3.1. Mechanical Properties of Gradient Specimens

Figure 5 reveals the development trend in mechanical properties of modified raw-soil-based wall materials when the inorganic modified admixtures have a gradient distribution and homogeneous distribution in raw soil materials. It can be seen from Figure 5 that the strength of the raw soil specimens increases with the increase in the content of inorganic modified materials, and the strength of the gradient distribution specimens is better than the corresponding homogenous distribution specimen. The strength of the modified raw soil specimens reaches the maximum value when the inorganic admixture content is 19 wt%. The 7 d compressive strength of the modified raw soil specimens with gradient distribution does not change significantly compared with the homogenous distributed specimens, while the 28 d strength is increased by 1.4% compared with the homogenous distributed specimens. The flexural strengths of the modified raw-soil-based gradient-distributed specimens reached 2.15 MPa and 3.3 MPa at 7 d and 28 d, respectively, which were 2.3% and 3.1% higher than those of the homogenous distribution specimens. On the one hand, the first layer of the gradient specimen is an aggregate-rich zone, and the content of the inorganic modified material in the first layer is larger than that of the homogenous specimens; the increase in the content is conducive to the development of strength. In addition, the first layer is the tensile zone, which can withstand greater impact force. In

the case of unchanged components and properties, the factors affecting the properties of composites are also structural. Due to the high proportion of the outer layer as the whole, the outer protective layer with good mechanical properties has a hoop effect, so the overall compressive strength has been improved to a certain extent [25]. The incorporation of modified jute further improves the crack resistance properties. On the other hand, the internal cohesion of the inorganic modified material in the homogenous distribution specimens is poor, the elastic modulus of each component is quite different, and great stress will be generated at the interface. Gradient-distributed specimens are vibration-shaped with layered batching. During the vibrating process, the layers diffuse and merge with each other, and the components cross each other. The content of the components on both sides of the interface is similar with little difference, which makes the continuous change of components better, thus enhancing the cohesiveness between gradient layers and reducing the residual stress [26], ensuring the mechanical properties of the materials without mutation, greatly alleviating the stress concentration, and making the mechanical properties change continuously.

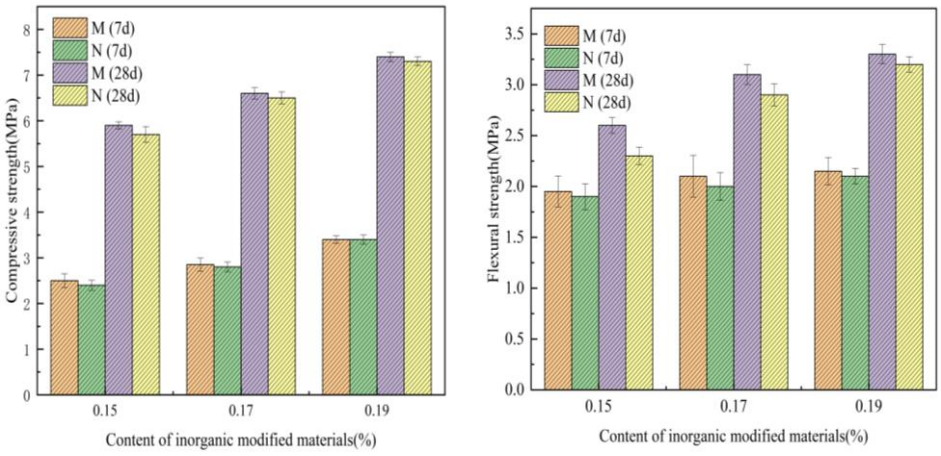


Figure 5. Effect of gradient modified material content on mechanical properties of raw-soil-based materials. (**a**) Compressive strength. (**b**) Flexural strength.

3.3.2. Thermal Conductivity

Figure 6 shows the variation in thermal conductivity of the gradient distribution specimen and homogenous distribution specimen of modified raw-soil-based material with different inorganic admixture contents and with or without jute fiber. It can be seen from Figure 6 that with the increase in inorganic admixtures in raw soil materials, the thermal conductivity of modified raw-soil-based wall materials increases, and the thermal insulation performance deteriorates. This is because, with the addition of admixtures, a large amount of gel will be produced in the hydration process, thus introducing a large number of small pores, which has a certain impact on its thermal insulation performance [6]. When the content of inorganic admixture is the same, the thermal conductivity of the gradient distribution specimens is generally smaller than that of the homogenous specimens. Due to the gradient specimen component having a gradient distribution, it can greatly reduce the temperature difference between the heat-generating layer and the non-heat-generating layer and the temperature stress [27], which is conducive to the internal heat of the material tending to be balanced, thus weakening the loss of thermal insulation function. The thermal conductivity of modified raw soil specimens can be further reduced by adding modified jute fibers to the specimen. The surface of the modified jute fibers is rough, as shown in Figure 7, and the bonding with the raw-soil-based wall material is strong, which makes the structure of the raw-soil-based wall material closer, and the pore channel of heat transfer is blocked; combined with the connection and toughening effect of jute fibers, the development of cracks can be delayed to a certain extent, and the heat transfer through crack convection can

be further reduced. At the same time, during the curing and drying process of the modified raw soil specimen, due to water loss, it is easy to form a water loss cavity around the jute. However, because the jute fiber is extremely slender, the introduction of harmful pores around it is extremely low. Therefore, it plays a positive role in the thermal insulation of raw-soil-based materials. This is similar to the conclusion of Ghosh [28]. After modification, jute fiber is similar to wool, soft and fluffy. The modified jute fiber is interconnected to form a network structure, which has a good thermal insulation function.

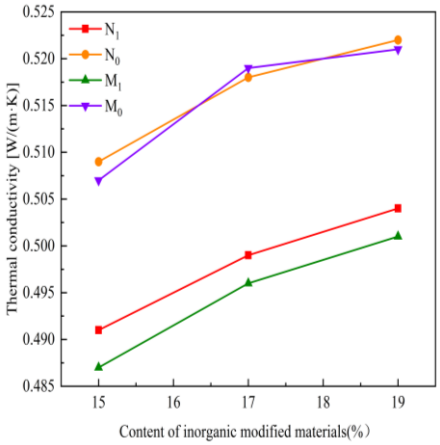
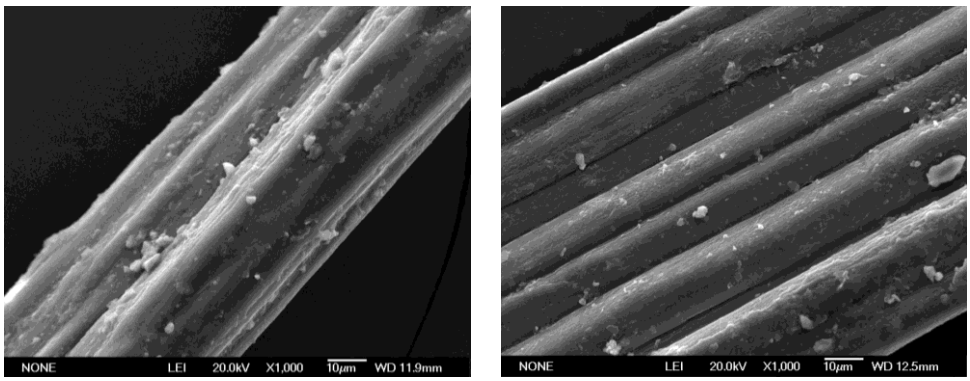


Figure 6. Effect of gradient modified material content on thermal conductivity of raw-soil-based materials (M_1 and M_0 represent the gradient distribution specimens with and without jute fibers, respectively. N_1 and N_0 represent homogenous distributed specimens with and without jute fiber, respectively).



(**a**) (**b**)

Figure 7. SEM images of jute fibers before and after modification. (**a**) Unmodified jute fiber. (**b**) Jute fiber modified with 5 wt% NaOH solution.

4. Conclusions

In this paper, the raw soil material was modified by inorganic admixture and jute fiber. By studying the gradient distribution and homogenous distribution of inorganic admixture in raw soil material, the influence of the gradient distribution and homogenous distribution of inorganic admixture in modified raw-soil-based wall material on its mechanical properties and thermal conductivity was analyzed. The relevant conclusions are as follows:

(1) The incorporation ratios of cement, fly ash and slaked lime in raw soil materials are 10 wt%, 6 wt% and 4 wt%, respectively. That is, when the incorporation ratio of the three admixtures is 5:3:2, the 28 d compressive and flexural strength reach 6.4 MPa and 2.9 MPa, respectively. The incorporation of modified jute fibers can further improve the mechanical properties. When the incorporation ratio of jute fibers is

0.8 v%, the compressive strength and flexural strength of the modified raw-soil-based wall material are increased by 22% and 24%, respectively.

(2) The compressive and flexural strength of modified raw-soil-based wall materials is positively correlated with the amount of inorganic admixture when the amount of modified jute is 0.8 v% and the total amount of inorganic admixture varies within the range of 12–22 wt%; the minimum compressive strength and flexural strength of the modified raw-soil-based wall materials at 28 d were 4.4 MPa and 2.5 MPa, respectively, which meet the requirements of mechanical properties of wall materials. Therefore, the gradient layers with a modified jute content of 0.8 v% and inorganic admixture in the range of 12–22 wt% are designed to meet the requirements of mechanical properties of the gradient design scheme.

(3) Gradient design can further improve the mechanical properties of modified raw-soil-based wall materials and weaken the loss of thermal insulation performance. With the combined effect of inorganic materials and jute fiber, the minimum compressive strength of the modified raw-soil-based wall material was 5.9 MPa, and the thermal conductivity was 0.501 W/(m·K), which was 3.5% and 4% higher than that of the raw soil material without inorganic material gradient modification, respectively. The highest compressive strength of ordinary sintered bricks is 3.94 MPa and the thermal conductivity of concrete structures and masonry mortar is generally above 0.75 W/(m·K), so the strength and thermal conductivity of the modified raw-soil-based wall materials designed by gradient in this paper meet the requirements of the masonry structure.

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References

1. Parracha, J.L.; Lima, J.; Freire, M.T.; Ferreira, M.; Faria, P. Vernacular earthen buildings from leiria, portugal architectural survey towards their conservation and retrofitting. *J. Build. Eng.* **2021**, *35*, 102115. [CrossRef]
2. Van Damme, H.; Houben, H. Earth concrete. Stabilization revisited. *Cem. Concr. Res.* **2018**, *114*, 90–102. [CrossRef]
3. Liu, J.; Wu, X.; Zhang, M.; Wang, S.; Hai, R. Influence of modification on characteristics of moisture transportation of earth materials. *J. Build. Mater.* **2018**, *21*, 1012–1016. (In Chinese)
4. Pacheco-Torgal, F.; Jalali, S. Earth construction: Lessons from the past for future eco-efficient construction. *Constr. Build. Mater.* **2012**, *29*, 512–519. [CrossRef]
5. Jayasinghe, C.; Kamaladasa, N. Compressive strength characteristics of cement stabilized rammed earth walls. *Constr. Build. Mater.* **2007**, *21*, 1971–1976. [CrossRef]
6. Yang, Y.; Zhang, N.; Zhang, L.; Rong, H.; Wei, C. Influence of modified materials on hygrothermal properties of raw soil block. *J. Build. Mater.* **2021**, *24*, 313–317+361. (In Chinese) [CrossRef]
7. Ciancio, D.; Beckett, C.T.S.; Carraro, J.A.H. Optimum lime content identification for lime-stabilised rammed earth. *Constr. Build. Mater.* **2014**, *53*, 59–65. [CrossRef]
8. Ma, C.; Xie, Y.; Long, G. A calculation model for compressive strength of cleaner earth-based construction with a high-efficiency stabilizer and fly ash. *J. Clean. Prod.* **2018**, *183*, 292–303. [CrossRef]
9. Burroughs, S. Soil property criteria for rammed earth stabilization. *J. Mater. Civ. Eng.* **2008**, *20*, 264–273. [CrossRef]
10. Liu, J.; Chu, J.; Zhao, J.; Yuan, D. Effect of admixtures on mechanical properties of raw clay material for wall. *J. Build. Mater.* **2010**, *13*, 446–451. (In Chinese) [CrossRef]
11. Danso, H.; Martinson, D.B.; Ali, M.; Williams, J.B. Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres. *Constr. Build. Mater.* **2015**, *101*, 797–809. [CrossRef]
12. Yetgin, Ş.; Çavdar, Ö.; Çavdar, A. The effects of the fiber contents on the mechanic properties of the adobes. *Constr. Build. Mater.* **2008**, *22*, 222–227. [CrossRef]
13. Liu, J.; Hai, R.; Zhang, M.; Zhang, L. Structure and properties of stabilized earth materials modified by plant fiber. *J. Build. Mater.* **2016**, *19*, 1068–1072. (In Chinese)

14. Qin, R.; Lau, D.; Tam, L.; Liu, T.; Zou, D.; Zhou, A. Experimental investigation on interfacial defect criticality of FRP-confined concrete columns. *Sensors* **2019**, *19*, 468. [CrossRef]
15. Tang, Y.; Qiu, W.; Chen, L.; Yang, X.; Song, Y.; Tang, J. Preparation of W–V functionally gradient material by spark plasma sintering. *Nucl. Eng. Technol.* **2020**, *52*, 1706–1713. [CrossRef]
16. Patil, R.; Joladarashi, S.; Kadoli, R. Studies on free and forced vibration of functionally graded back plate with brake insulator of a disc brake system. *Arch. Appl. Mech.* **2020**, *90*, 2693–2714. [CrossRef]
17. Yu, H.; Liu, Y.; Hu, Y.; Ta, M. Experimental study on the effect of gradient interface on the mechanical properties of Cu/WCP functionally gradient materials using digital image correlation technique. *Materials* **2022**, *15*, 4004. [CrossRef]
18. Yu, Q.; Huang, Z.; Hu, W.; Wang, Y.; Wang, H.; Li, X.; Zhuang, W.; Wang, L.; Zhou, Y. High strength and toughness of in-situ TiC/In718 functionally gradient material by using Ti_3AlC_2 as a precursor. *J. Alloys Compd.* **2022**, *920*, 165962. [CrossRef]
19. *GB/T 17671-2021*; Test Method of Cement Mortar Strength (ISO Method). Standardization Administration and the State Administration for Market Regulation of China: Beijing, China, 2021.
20. Deng, Z.; Chen, L. Gradient design and stress analysis of functionally gradient materials. *J. Shenyang Ligong Univ.* **2016**, *35*, 73–77+90. (In Chinese) [CrossRef]
21. Shen, B.; Hubler, M.; Paulino, G.H.; Struble, L.J. Functionally-graded fiber-reinforced cement composite: Processing, microstructure, and properties. *Cem. Concr. Compos.* **2008**, *30*, 663–673. [CrossRef]
22. *GB/T 10294-2008*; Determination of Steady-State Thermal Resistance and Related Characteristics of Thermal Insulation Materials-Protection Hot Plate Method. Standardization Administration and General Administration of Quality Supervision, Inspection and Quarantine of China: Beijing, China, 2008.
23. Kim, Y.; Kim, H.; Lee, G. Mechanical behavior of lightweight soil reinforced with waste fishing net. *Geotext. Geomembr.* **2008**, *26*, 512–518. [CrossRef]
24. Ferreiro, S.; Herfort, D.; Damtoft, J.S. Effect of raw clay type, fineness, water-to-cement ratio and fly ash addition on workability and strength performance of calcined clay—Limestone portland cements. *Cem. Concr. Res.* **2017**, *101*, 1–12. [CrossRef]
25. Su, Y. Gradient Structure Design and Co-Extrusion Peparation of Cement-Based Insulation Materials with Graded Structure. Master's Thesis, South China University of Technology, Guangzhou, China, 2015. (In Chinese).
26. Li, D.; Chen, H.N.; Xu, H. The effect of nanostructured surface layer on the fatigue behaviors of a carbon steel. *Appl. Surf. Sci.* **2009**, *255*, 3811–3816. [CrossRef]
27. Hai, R.; Pan, H.; Zhang, Y.; Wu, K. Effect of carbon fiber gradient distribution on the electro-thermal properties of cement mortar. *J. Build. Mater.* **2009**, *12*, 332–335+351. (In Chinese) [CrossRef]
28. Ghosh, S.; Singh, S.; Maity, S. Thermal insulation behavior of chemically treated jute fiber quilt. *J. Nat. Fibers* **2021**, *18*, 568–580. [CrossRef]

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