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Laboratory experimental study on red mud geopolymer used as road subgrade materials

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Abstract. Red mud is a strong alkaline waste discharged from the process of alumina extraction, which is harmful to the environment and its utilization rate is always low. One of the effective ways to utilize red mud is used as road subgrade material. In this paper, the industrial wastes including red mud, fly ash, slag, and desulfurized gypsum are used as basic raw materials to prepare subgrade filling materials. A series of laboratory tests, such as compaction test, California Bearing Ratio (CBR) test (soaked and non-soaked conditions) and permeability test, are carried out. The physical and mechanical properties, such as maximum dry density, optimum moisture content, CBR value, expansion, permeability coefficient and soaked strength loss rate, of the mixtures with different proportions, were studied. The results can provide reference for the selection of the best proportion scheme and promote the utilization of red mud in subgrade engineering.

1 Introduction

With the continuous development of China's economy, a large number of industrial solid wastes are produced in industrial production every year. According to the statistics of relevant departments, nearly 2 billion tons of industrial solid waste are produced every year in China. Red mud is a strong alkaline waste residue discharged from alumina production. 1.0 ~ 2.0 t red mud should be produced at the same time for every 1 t alumina production. At present, the amount of red mud is huge, and it is still increasing. It takes up a lot of land resources and causes serious pollution to the environment. Besides, as a by-product of the rapid development of flue gas desulfurization industry in thermal power plants, desulfurization gypsum has become another large solid waste in thermal power plants after fly ash. This kind of industrial waste discharge has caused many adverse effects on human production and life, and seriously restricted the sustainable development of ecological environment.

At the same time, with the rapid development of infrastructure construction, the demand for land resources is increasing. For example, the highway takes up a lot of land resources, and the traditional road subgrade construction needs a lot of earthwork. With the continuous improvement of the awareness of ecological environment and land resources protection, it is urgent to develop new environmental protection materials for road construction in order to reduce earth mining. If red mud and other solid wastes can be used in road subgrade filling, it can not only consume and utilize red mud and other solid wastes on a large scale, but also save earthwork resources, which meets the strategic requirements of national environmental protection and sustainable economic and social development.

Using red mud as road material is one of the effective ways to consume a lot of red mud, which has been studied by some scholars. For example, Wang [1] studied the technical performance of red mud used as road material and analyzed its comprehensive benefits. Fu et al. [2,3] determined the red mud ratio scheme suitable for road subgrade and surface layer through experiments, and studied the corresponding pavement construction method and forming technology. Yang et al. [4] carried out the research on the test and engineering application of red mud used in road subgrade, and built a 4 km long demonstration highway with subgrade made of sintering red mud. Liu et al. [5] used Bayer red mud, coal gangue, fly ash and other industrial solid wastes as basic raw materials to prepare a kind of highway pavement base material in the laboratory, and studied its mechanical properties, durability and environmental performance.

Generally speaking, the research on red mud used as road subgrade is still in its infancy, and the pavement performance of red mud geopolymer needs further study. In this paper, red mud, fly ash, desulfurized gypsum and other industrial wastes are used as basic raw materials to prepare geopolymer as subgrade material. A series of laboratory tests were carried out to study its physical and mechanical properties, aiming to further clarify the pavement performance of red mud geopolymer and then promote its engineering application.

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2 Materials and methods

2.1 Raw materials

Previous studies [6-10] have shown that red mud and fly ash can form geopolymer under the action of certain activator. Different strength can be obtained by adjusting different proportion and activator, mixing with appropriate water cement ratio and curing enough age under specific conditions, which can meet the requirements of different construction projects.

The main raw materials are red mud, fly ash, desulfurization gypsum and slag. The red mud is taken from No.2 red mud storage of Xinfa alumina plant in Shandong Chiping, and other materials are taken from Xinfa power plant. The raw materials were analyzed by XRD, and the chemical composition of red mud and fly ash is shown in Table 1.

Table 1. Chemical composition of red mud and fly ash.

Chemical composition	Red mud /%	Fly ash /%
SiO_2	25.58	49.1
Al_2O_3	26.4	38.7
Fe_2O_3	23.26	6
CaO	1.33	1.8
Na_2O	14.98	0.2
MgO	0.15	0.4
K_2O	0.21	0.8
SO_3	0.8	1.1

In addition, the main phase of desulfurization gypsum is $CaSO_4 \cdot 2H_2O$, and the main phase of slag is $Al_{2.3}Si_7O_{4.85}$. It can be seen that red mud and fly ash are rich in silica and alumina, and desulfurization gypsum and slag also contain a large number of calcium ions, aluminum ions and silicon ions, which provide a material basis for their preparation of geopolymer. At the same time, red mud is strongly alkaline, which can promote the production of geopolymer.

2.2 Testing program

In order to determine the economical and applicable proportion of subgrade materials, and to compare the interaction between different raw materials, various material ratio schemes are designed, as shown in Table 2.

The test items for different proportioning schemes mainly include compaction test, California Bearing Ratio (CBR) test (for soaked and non-soaked samples) and permeability test. The test indexes include maximum dry density, optimum moisture content, CBR value, expansion, permeability coefficient and immersion strength loss rate.

The compaction test was carried out in accordance with test specification JTGE51-2009 [11]. Five samples with different water content were prepared according to the difference of 1% ~ 1.5% in turn. The samples were soaked for one day and night, and the maximum dry density and optimal water content of each proportion of materials were measured. For different proportioning schemes, compaction samples were prepared according to the optimal moisture content measured respectively, and CBR test and permeability test were carried out according to the test code JTGE40-2007 [12].

Table 2. Proportioning test scheme.

No.	Red mud/%	Fly ash/%	Slag/%	Gypsum /%
1	100	0	0	0
2	75	25	0	0
3	50	0	50	0
4	40	0	60	0
5	30	0	70	0
6	60	0	20	20
7	40	0	40	20
8	20	0	50	30
9	20	0	60	20
10	20	0	70	10
11	60	20	20	0
12	40	40	20	0
13	40	20	40	0
14	60	20	0	20

For each proportion listed in Table 2, two groups of samples were prepared considering soaked and non-soaked conditions. One group was soaked in water for 4 days and nights, and the other group was not soaked in water. In the CBR test, the initial reading of the dial indicator of the soaked sample and the reading at the end of soaking were read respectively, by which the sample expansion was calculated. The strength loss rate of the soaked sample is reflected by comparing the CBR of soaked and non-soaked samples, based on which the water stability of the material was characterized. Besides, the permeability coefficient of the compacted sample was measured by the variable head permeability test, reflecting permeability of the subgrade materials.

3 Results and discussion

3.1 Compaction test

The maximum dry density and optimal moisture content of different proportioning schemes are measured through compaction test, and the results are shown in Table 3. It can be seen that the maximum dry density of mixed materials is between 1.03-1.51g/cm^3, which is relatively small comparing to that of conventional soils, while generally, the maximum dry density of silt, clay and sand is 1.61-1.80g/cm^3, 1.58-1.70g/cm^3 and 1.80-1.88g/cm^3, respectively. Obviously, this is directly related to the density of the material itself, while it is also related to other properties of the material. For example, the density and particle size of different materials will have an impact on the maximum dry density of the mixture. In practical terms, the slag density is 0.88g/cm^3, the fly ash density is 2.08g/cm^3, and the density of desulfurization gypsum is 2.28g/cm^3. With the increase of slag content, the maximum dry density and optimal moisture content of the mixture decrease. The maximum dry density of the mixture can be increased with the addition of fly ash or gypsum. The maximum dry density can be obtained with the addition of fly ash and gypsum in red mud (scheme No. 14). This may be due to, on the one hand, the high density of the material itself with fine particles (relative to the slag); on the other hand, the three materials have the possibility of polymerization, forming a more compact internal structure, which makes the density increase.

Table 3. Maximum dry density and optimum moisture content of different proportioning schemes.

No.	Maximum dry density /(g/cm^3)	Optimum moisture content /%
1	1.32	32.6
2	1.34	34.2
3	1.18	25.5
4	1.12	21.2
5	1.05	19.2
6	1.49	26.9
7	1.31	31.3
8	1.18	31
9	1.06	19
10	1.03	17.4
11	1.18	37.7
12	1.22	35
13	1.2	29.9
14	1.51	28

3.2 CBR test

The results of CBR test are shown in Figure 1, and the strength loss rate of soaked sample and its expansion are shown in Table 4.

Figure 1 shows that the CBR of all test schemes are greater than 8%, which meets the requirements of the minimum CBR of subgrade filler in all subgrade application parts [13]. It also can be seen that, the addition of slag can greatly improve the CBR of the mixture, considering that the slag plays a good skeleton role in the mixture and increases the bearing capacity of the mixture. From the comparison of the CBR under soaked and non-soaked conditions, it can be seen that the CBR of the mixture under the non-soaked condition is relatively large and the minimum value is 29.8%, while the maximum is close to 100%. Under the soaked condition, the CBR of most schemes are reduced to different degrees, which means the loss rate of soaked strength is different.

Table 4 illustrates that the soaking strength loss rate of pure red mud (i.e., No. 1 test scheme) is the highest, indicating that the water stability of pure red mud is very poor. After adding fly ash and gypsum, the strength loss rate decreases and the water stability improves to a certain extent. With the increase of slag content, the strength loss rate decreases obviously while the water stability of the mixture is improved very well. The addition of fly ash and gypsum can polymerize with red mud to a certain extent to form stable geopolymer and promote the improvement of water stability. When slag is added as coarse aggregate, some of its components can react with other materials. At the same time, it plays a positive role in promoting the compactness and overall stability of the mixture.

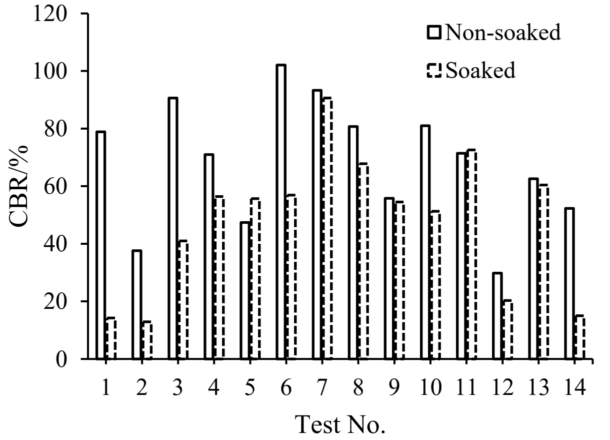

Fig. 1. CBR results of different schemes under two conditions.

Table 4. Strength loss rate of soaked sample and expansion of different proportioning schemes.

No.	Strength loss rate /%	Expansion /%
1	82	0.21
2	66	0.5
3	55	0.08
4	21	0
5	-18	0.16
6	44	0.1
7	3	0.18
8	16	0.25
9	2	0.1
10	37	0.2
11	-2	0.25
12	32	0.6
13	4	0.58
14	71	0.54

3.3 Permeability test

See Table 5 for the permeability coefficient of mixture of different schemes measured by variable head permeability test. It can be seen that the permeability coefficient of pure red mud is the smallest, which is close to that of clay (generally less than 1.2×10^{-6} cm/s) [14]. The permeability coefficient of scheme No. 5 is the largest with the highest slag content. In fact, the permeability coefficient of this mixture is similar to that of medium sand (6.0 × 10-3 ~ 2.4 × 10^{-2} cm/s) [14].

It's not hard to find out that, the permeability coefficient of the mixture increases with the addition of waste residue. Among them, the influence of slag is the most significant, followed by gypsum, and fly ash is the least. This can be explained from the following two aspects: (1) The influence of particle size and structure of different materials. The slag has a porous structure with large particle size, which can form a good permeability channel and increase the permeability coefficient of mixture. (2) The hydrophilicity of different materials is different, which affects the change of permeability of different mixtures.

Table 5. Permeability coefficient of different proportioning schemes.

No.	Permeability coefficient /(cm/s)	No.	Permeability coefficient /(cm/s)
1	3.5×10^{-6}	8	1.4×10^{-3}
2	7.8×10^{-6}	9	3.9×10^{-3}
3	1.2×10^{-3}	10	4.4×10^{-3}
4	6.4×10^{-3}	11	4.2×10^{-5}
5	6.8×10^{-3}	12	1.4×10^{-4}
6	2.8×10^{-4}	13	3.1×10^{-4}
7	4.4×10^{-4}	14	2.6×10^{-5}

4 Conclusions

Through laboratory tests, the maximum dry density, bearing ratio, loss rate of immersion strength, expansion and permeability coefficient of geopolymer mixture formed by red mud, fly ash, gypsum and slag were studied. On the whole, the pavement performance of the mixed material that with appropriate proportion is better than that of pure red mud, and the strength parameters such as bearing ratio and strength loss rate are improved. Consequently, the red mud based geopolymer used as subgrade material has good bearing capacity and water stability, and the expansion of the mixed material is very small, so the problem of soaking expansion can not be considered.

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