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Preparation and Performance of Geopolymer Pervious Concrete in Red Mud Slag Base

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Abstract. Pervious paving is an essential element of sponge city construction. However, regular previous cement concrete only has a minimal filtering effect on surface runoff, and the preparation process produces significant amounts of carbon dioxide. Slag-based geopolymer pervious concrete has great mechanical qualities, being energy efficient and eco-friendly. Red mud is an alkaline residue released during the alumina refining process from bauxite mining, and there is no known way to treat it. This paper investigates the effects of red mud content, aggregate gradation, and alkali exciter content on the performance of red mud slag-based geopolymer pervious concrete (RMSGPC) through orthogonal experiments. It is discovered that the right red mud content can not only promote colloidal reaction but also remove heavy metal ions. Multi-graded aggregates can provide a better performance, and alkali exciter mainly has the greatest effect on mechanical properties.

Keywords. Pervious concrete; red mud; slag-based geopolymer ;purification performance; orthogonal test; microscopic analysis

1. Introduction

The degradation of surface water can be brought on by pollutants and trash produced by moving vehicles [1]. These pollutants can also increase the pollutant loads in road runoff. In the United States, dangerous heavy metals such as copper, lead, and zinc were discovered in road runoff in the 1980s. Runoff contains lead, copper, and cadmium in ionic form because of the low pH [2]. Shi et al. [3] discovered that most rainfall in China had a moderately high heavy metal pollution load and that stormwater runoff contained a range of heavy metal ions, including dissolved and particulate Cd, Pb, Cu, and Zn.

Red mud, an insoluble alkaline waste product released during the extraction of alumina from bauxite mines, is typically dumped in open piles and has the potential to have a permanent negative influence on the environment. Researchers at home and abroad have studied the effectiveness of red mud as a road construction material since the 1950s. Red mud was utilized as a filler in asphalt pavements in Germany and Japan, and it was employed as a gravel base for road pavements in the former Soviet Union to

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increase performance [4]. By conducting testing indoors, Liang et al. [5] proposed that red mud might partially replace the cement dosage while creating concrete examples.

Pervious concrete's inherent porosity makes it able to filter and clean contaminants out of stormwater runoff [6]. Yang [7] discovered that when diatomaceous earth was put to geopolymer pervious concrete, the greatest rates of total phosphorus removal, heavy metal removal, and suspended matter removal were 87.23%, 85.73%, and 77.46%, respectively. Jia et al. [8] showed that when chitosan was added to geopolymer pervious concrete, the removal rate of Pb^{2+} increased to 97.76% at a 1.0% chitosan incorporation and that the pervious concrete's mechanical qualities were also strengthened.

In order to explore the impact of the modification of each factor on the overall performance of red mud slag-based permeable concrete and to suggest an ideal ratio for RMSGPC, orthogonal tests were conducted utilizing various red mud content, aggregate gradations, and alkali exciter content.

2. Test

2.1. Test Materials

Aggregate: ① 2.36-4.75 mm pyrochlore aggregates; ② 4.75-9.5 mm pyrochlore aggregates; ③ 9.5-13.6 mm pyrochlore aggregates. Mineral powder: S95 grade mineral powder produced by Guangzhou Conghua Jiangpu Fine Mineral Powder Plant. Red mud: Bayer red mud from Guangxi Pingguo Aluminium Plant. The red mud used in the test was dried at 105°C and then ground with a mill to make the particle size less than 0.075 mm. The chemical composition of this red mud is shown in Table 1. Sodium silicate (density: 1.278 g/cm^3; purity: 26.88%) was purchased from Guangdong Sihui Haoshun Water Glass Co. Sodium hydroxide. NaOH (pH>11; purity: 99%) was purchased from Fuchen (Tianjin) Chemical Reagent Co.

Table 1. Chemical composition of the red mud

Grouping	Fe_2O_3	Al_2O_3	CaO	SiO_2	TiO_2	Na_2O	Remaining elements
Content Capacity (%)	30.95	18.87	13.78	12.08	6.87	6.2	2.12

2.2. Design Methodology

In order to assure the test's validity and produce more precise results, the orthogonal design of the test chooses a representative level of components. The performance of RMSGPC is directly impacted by the quantity of alkali stimulants and red mud. ZHANG X X [9] establishes a reference range for aggregate gradation for various particle sizes and demonstrates how altering the aggregate gradation can enhance the mechanical properties of permeable concrete. Alkali excitant dosage should be between 18% and 26%, according to Zhu He's study [10]. For the orthogonal testing of RMSGPC in this study, the doses of alkali excitant are 21%, 24%, and 27%.

The RMSGPC orthogonal test was therefore carried out with the red mud content, aggregate gradation and alkali exciter content levels as shown in Table 2. 28d compressive strength, 28d flexural strength, porosity, effective porosity factor and heavy metal removal rate of the specimens were used as test indicators to evaluate the effect of each factor on the performance of RMSGPC.

In this paper, the volumetric method of permeable cement concrete is used to design the RMSGPC. The target porosity was set at 15%, and the water-cement ratio was assumed to be 0.35 [7].

Table 2. RMSGPC orthogonal test variables level

Variables level	Red mud content (%)	Aggregate grading	Alkali exciter content (%)
1	10	G1	21
2	15	G2	24
3	20	G3	27

(G1: 100% 4.75-9.5 mm aggregate; G2: 10% 2.36-4.75 mmaggregate, 80% 4.75-9.5 mm aggregate, 10% 9.5-13.2 mm aggregate; G3: 10% 2.36-4.75 mm aggregate,90% 4.75-9.5 mm aggregate.)

2.3. Specimen Preparation

It is critical to ensure that the cementitious material adheres to the aggregate and that a specific pore structure is maintained when forming pervious concrete. Firstly, the pervious concrete is created. Then the alkali exciter is prepared according to the prepared proportions. Once the alkali exciter has cooled to room temperature, the aggregate is mixed with 20% of water for 30 seconds to ensure that the surface of the aggregate contains a certain amount of hydraulic cementing material for adhesion. Next, 50% of silica-alumina raw materials (mineral powder and red mud), 50% of alkali exciter, and 40% of water are added. After that, water, alkali stimulant, and the remaining silica-alumina raw materials are added, and all those components are mixed for 60 seconds and then discharged.

2.4. Test Method

The compressive and flexural strength tests of RMSGPC were performed in accordance with the "Standard for Mechanical Properties of General Concrete" test methods. [11]

The RMSGPC permeability coefficient was measured by a self-designed water permeability testing apparatus. A cubic specimen of the same size as the compressive specimen was used for the test. The permeability coefficient can be calculated by Eq. (1), and the testing apparatus is shown in Figure 1.

$$k_T = \frac{QL}{AHt} \tag{1}$$

where k_T is the permeability coefficient (mm/s); Q is the amount of water seeped out in time (mm^3); L is the thickness of the specimen (mm); A is the surface area of the specimen (mm^2); H is the height difference (mm); t is the time (s).

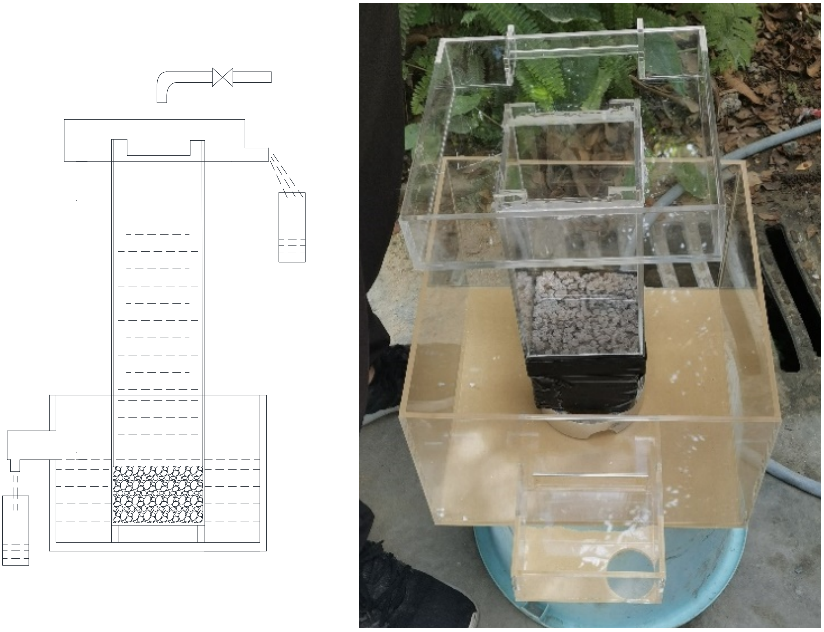


Figure 1. Home-made water permeability tester

By using the weight approach, the RMSGPC's effective porosity was evaluated. The test sample is weighed M_1 (g) and measured for volume V (m^3) before being dried in an oven set at 105 °C. The wire cylinder is then entirely submerged in water, and its weight in water, M_2 (g), is noted. The test specimen is then weighed M_3 (g) after being inserted into the wire cylinder to make sure it is completely submerged in water. Finally, Eq. (2) is used to determine the effective porosity P.

$$P = \left(1 - \frac{(M_3 - M_2) - M_1}{V}\right) \times 100\% \tag{2}$$

The removal efficiency of the heavy metals Cu^{2+}, Pb^{2+}, and Cd^{2+} was used in this paper to investigate the efficacy of RMSGPC in the purification of wastewater runoff. The content of each heavy metal ion was determined using an atomic absorption spectrophotometer.

Microscopic analyses were carried out using high-resolution field emission scanning electron microscopy (SEM) at the Test Centre of South China University of Technology (SCUT) to investigate the mechanism of the mechanical and purification properties of RMSGPC.

3. Results and Analysis

Table 3 shows the test results for 28d compressive strength, 28d flexural strength, permeability coefficient, effective porosity and heavy metal ion purification for the nine specimens with different proportions.

3.1. Mechanical Performance Analysis

The compressive strength test results of all test groups met the requirements of the Technical Specification for Permeable Cement Pavements [12] for the mechanical properties of C20 permeable concrete.

It can be seen from Figure 2 that alkali exciter content was found to have the greatest impact on the 28d average compressive strength, followed by aggregate grading and red mud content, while alkaline exciter admixture has the greatest effect on the 28d average flexural strength, followed by the amount of red mud content and aggregate gradation. The mechanical properties of RMSGPC are found to be most influenced by alkali exciter dosage, and the trend is consistent for each factor at various doses.

However, when the amount of red mud increases, the geopolymer's ability to polymerize will be hindered, and the silica-alumina material will not be able to adequately fill the pores, reducing the RMSGPC's mechanical characteristics. The average 28d compressive and flexural strengths of aggregate grade 3 were the highest of the three aggregate grades. The bigger pores in the permeable concrete are filled with a tiny amount of 2.36-4.75 mm small-size aggregate, which increases the number of small pores and decreases the number of large pores. The mechanical properties of RMSGPC are enhanced by the filling of tiny-size aggregates because it expands the contact area and increases the friction between the aggregates.

Table 3. Results of RMSGPC experiments

Tests Group	28d Pressure strength (MPa)	28d Flexural strength (MPa)	Water permeability (mm/s)	Effective porosity (%)	Cu^{2+} Purification rate (%)	Pb^{2+} Purification rate (%)	Ca^{2+} Purification rate (%)
ZJ-1	21.21	4.07	6.27	16.13	72.79	70.73	65.35
ZJ-2	25.16	5.39	6.35	15.83	77.60	76.34	73.18
ZJ-3	24.13	4.54	6.40	17.55	83.08	82.07	83.76
ZJ-4	21.69	4.29	5.02	14.05	76.73	73.17	76.25
ZJ-5	24.10	5.01	5.39	15.81	82.69	81.28	79.81
ZJ-6	25.91	5.58	5.83	15.45	78.37	76.65	72.78
ZJ-7	23.13	4.14	4.36	12.05	83.17	80.98	75.20
ZJ-8	26.05	5.09	4.38	13.59	77.79	74.09	76.17
ZJ-9	30.13	5.71	4.68	14.36	79.52	81.34	80.05

With the increase in alkali exciter dose from 21% to 27%, the RMSGPC's 28d average compressive strength and flexural strength rose. A fuller reaction, more gelation, better bonding of the aggregate, and enhanced strength are all brought about by the silica-alumina material being stimulated to a larger extent with increasing alkali exciter content. A certain quantity of alkali exciter causes part of the free silicate ions to precipitate out as amorphous silicic acid, slowing down the polymerization reaction.

3.2. Water Permeability Analysis

The order of influence of the factors on the permeability of RMSGPC is aggregate gradation > alkali exciter content > red mud content (Figure 3). The water permeability of RMSGPC tends to drop initially before increasing, but the overall fluctuation is tiny 3% as the amount of red mud increases. The RMSGPC with a single grade (Grade 1) has a higher permeability than the RMSGPC with Multi-grades (Grades 2 and 3), where the large pores between the aggregates are easily filled by the small-size aggregates and the contact points between the aggregates are increased, resulting in a more circuitous water penetration path through the cementitious material, which affects the permeability of the concrete. The quantity of RMSGPC steadily increases its permeability. As the concentration of alkali exciter rises, RMSGPC's permeability gradually increases. The effective porosity varied within 12.14% and the permeability coefficient within 8.04% in the alkali exciter range of 21% to 27%.

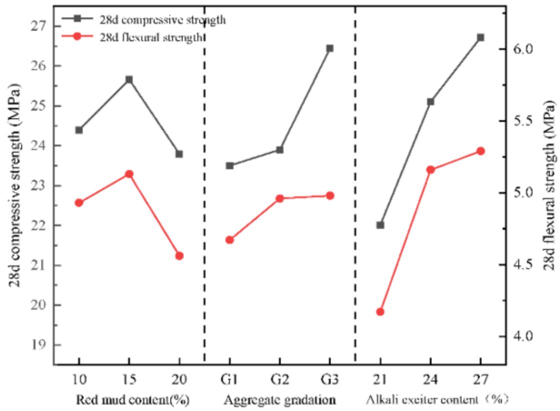


Figure 2. Visual effects of compressive and flexural strengths of RMSGPC

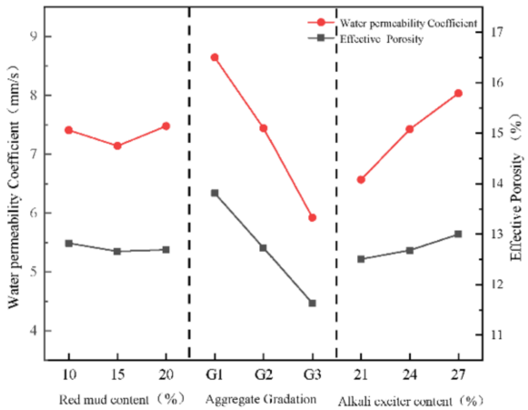


Figure 3. Visual effects of RMSGPC water permeability

3.3. *Purification Performance Analysis*

The order of each component's impact on the pace of purification of the three heavy metal ions was red mud content > alkali exciter content > aggregate gradation (Figure 4). The primary method used by RMSGPC to remove heavy metal contaminants is chemical complexation. However, physical adsorption also contributes to the process. The purification rate of Cu^{2+}, Pb^{2+}, and Cd^{2+} exhibits an upward trend as red mud inclusion increases. Red mud as an alkaline substance in some of the RMSGPC is not used in the polymerization process, some hydroxide is present in the RMSGPC leachate, where it combines with heavy metal ions to produce precipitates. The number of hydroxide ions that can be delivered increases with the amount of red mud content, creating a weakly alkaline environment favorable for the combination of hydroxide ions with heavy metal ions to produce precipitates.

Although not significantly, aggregate grading affects the purification rates of Cu^{2+}, Pb^{2+}, and Cd^{2+}. In the RMSGPC specimens, the heavy metal ions interacted with the hydroxide that had been leached to create hydroxide ion precipitates. In comparison to the single grade, the Multi-grade RMSGPC's interior pore structure was denser, making it more effective at capturing hydroxide ion precipitate.

With higher doses of alkali exciter, the rate at which heavy metal ions are cleaned up by RMSGPC rises. According to Androniuk et al. [13], the geopolymer gel also appears to have some capacity for adsorbing heavy metal ions. When the alkali exciter dose rises, more geopolymer gels are created, increasing the RMSGPC's ability to adsorb heavy metal ions.

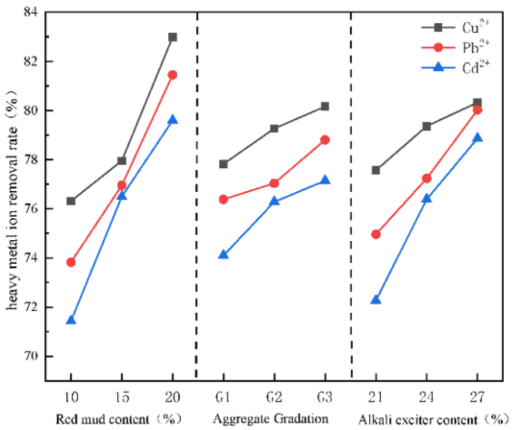


Figure 4. Visual effects of heavy metal ion removal by RMSGPC

4. Micromechanics of Polymeric Permeable Concrete on Red Mud Slag Base

4.1. XRD Analysis of RMSGPC

Figure 5 shows the results of the XRD diffraction examination of the mineral powders, red mud, and ZJ-9 at 28d. Calcite and other elements are primarily present in the mineral powders, and calcite, Katotie, and Gibbsite are primarily present in the red mud. The distinctive hematite diffraction peak is significant at 2θ=35.5°, and it has been discovered that a 15% hematite admixture has a hematite diffraction peak that is noticeable at 35.5°(C). In comparison to A and B, C has a greater dispersion peak package near 29.4°, which helps to explain why the C-S-H gel formed after the geopolymer reaction was involved. The reaction in the RMSGPC slurry results in the production of many silica-aluminates, including the zeolite minerals C-S-H gels and Katoite. The $[AlO_4]^{4-}$ and $[SiO_4]^{4-}$ tetrahedra on the surface of the mineral particles allow for enhanced chemical bond formation in the structure of the zeolite. It might improve the mechanical qualities of RMSGPC.

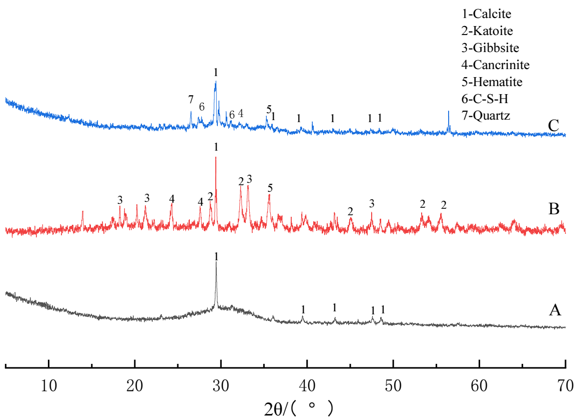
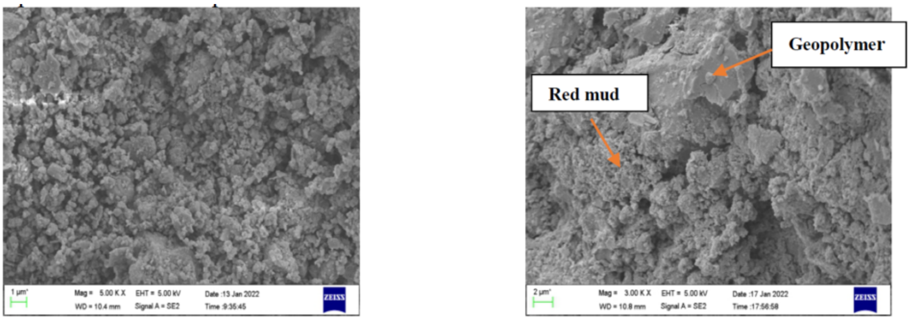


Figure 5. XRD diffractogram (A - mineral powder, B - red mud, C - ZJ-9)

4.2. *SEM Analysis of RMSGPC*

The microscopic red mud particles, which can be seen in Figure 6(a), are found to be irregularly fine, with the majority of them being smaller than 1 μm. They are primarily rounded or irregular crystalline blocks, closely packed on the surface of larger particles, with an uneven surface, no complete platelet structure, and a few pores. It is clear from Figure 6(b) that some of the red mud is connected to the geopolymer in the form of particles and is not a part of the polymerization reaction of the geopolymer.

That shows that some of the red mud is visible on the RMSGPC slurry's surface and is not covered by the geopolymer cementing substance. The red mud system also has a negative charge, and it is better able to adsorb heavy metal ions when the red mud raises the ambient pH of the geopolymer cementing material system[14]. The red mud supplies carboxyl and hydroxyl groups to form complexes with the pollutants for adsorption.



(a) Red mud (5000 x) (b) RMSGPC (5000 x)

Figure 6. Microscopic morphology of RMSGPC

5. Conclusion

In this paper, the following conclusions can be drawn from the orthogonal test analysis of red mud content, aggregate gradation, and alkali exciter content.

(1) Of the three variables, the height of the aggregate gradation considerably affects the permeability of RMSGPC, the quantity of alkali exciter content significantly affects the mechanical characteristics of RMSGPC, and the amount of red mud content does not significantly impact either.

(2) The rate at which RMSGPC removes pollutants rises as more red mud is dosed. Single grade

(Grade 1) RMSGPC has a significantly lower clean-up rate than Multi-grade (Grades 2 and 3) RMSGPC. The amount of alkali exciter has a minimal impact on the clean-up performance of RMSGPC, although the clean-up rate of RMSGPC steadily increases as the amount of alkali exciter grows.

(3) A SEM microscopic investigation reveals that some of the red mud is adhered to the surface of the geopolymer slurry as particle form and is not involved in the polymerization of the geopolymer.

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