

EXPERIMENTAL STUDY ON BASIC PROPERTIES OF PLASTIC CONCRETE WITH GS SOLIDIFIED MATERIAL

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Abstract. It is common for industrial wastes such as slag, steel slag and fly ash to replace cement in plastic concrete. GS solidified material is prepared by mixing the three in a certain proportion. What is the basic performance of GS solidified material plastic concrete? In view of this problem, the mix proportion design is carried out, based on the unconfined compressive strength test and improved flexible wall permeability test. The basic properties of GS solidified plastic concrete were studied. The results show that the fluidity increases with the increase of the water binder ratio and decreases with the increase of the bentonite content. The unconfined compressive strength and permeability coefficient decreases with the increase of the bentonite content, but the decrease is not obvious. The unconfined compressive strength increases with the decrease of the water binder ratio or the increase of age, at the age of 14 days the increase is large, and at the age of 28 and 60 days, the increase decreases with the increase of the bentonite content. The permeability coefficient decreases with the decrease of the water binder ratio. When the water binder ratio decreases from 1.9 to 1.7, the permeability coefficient improves greatly, from less than 10^{-7} cm·s⁻¹ to 10^{-8} cm·s⁻¹. There is an inflection point between 13 and 18 days, before that, the permeability coefficient decreases rapidly, and then tends to be flat. When the water binder ratio is greater than or equal to 1.9, the permeability coefficient decreases slowly without the inflection point.

Keywords: plastic concrete, GS solidified material, permeability coefficient, unconfined compressive strength, fluidity

Introduction

According to the survey of BP world energy statistical yearbook in 2021, China's carbon emissions continued to grow for the fourth consecutive year in 2020, with an increase of 0.6%, and its share in the total global carbon emissions increased to 31%. As a major carbon emitter, the cement industry accounts for 7% of the global carbon dioxide emissions. Slag, steel slag and fly ash as industrial wastes instead of cement have become the main method to solve this problem. GS solidified materials came into being on this basis.

GS solidified material is composed of 70% slag micro powder, 5% steel slag micro powder, 4% fly ash, 20% cement and 1% desulfurization products. It can be used for soft foundation reinforcement, temporary retaining the structure of deep foundation pit, backfill material and concrete preparation. Plastic concrete is widely used in water conservancy and hydropower projects, deep foundation pit projects, sewage treatment projects and landfill restoration projects because of its large fluidity, low elastic modulus and good impermeability [1-2].

There are many studies on the working performance, compressive performance and impermeability of plastic concrete mixed with slag, steel slag and fly ash [3-8]. Wu Haoliang [9] excited slag bentonite with magnesium oxide to obtain a vertical barrier with 28 d strength meeting the design requirements of 100 kPa. Under the action of tap water and sodium sulfate contaminated solution, the permeability coefficient meets anti seepage requirements of 1×10^{-6} cm·s⁻¹. Wu Weijuan [10] found that after hydration for 12 hours, the structural compactness of the slurry decreases with the increase of the steel slag content. When the steel slag content reaches 40%, the slurry cannot be hardened. A large number of test results show that the single addition of slag, steel slag and fly ash cannot achieve good results, so the multi-component composite cementitious material is studied. Li Yunfeng et al. [11] found that the cohesion and water retention of fresh concrete are improved after single mixing of steel slag powder. When steel slag powder and slag powder are mixed together, the higher the proportion of steel slag powder, the better the fluidity of the mixture. Li Hongyan et al. [12] found that replacing some cement with fly ash and slag has lower early compressive strength than cement paste with the same water cement ratio, but the later strength increases faster. Many studies also show that replacing part of cement with blast furnace slag and fly ash can improve the chemical corrosion resistance of plastic concrete [13-16].

Therefore, it is theoretically feasible to mix slag, steel slag and fly ash into GS curing material and apply it to plastic concrete.

In conclusion, through the mix proportion design, fluidity test, unconfined compressive strength test and improved flexible wall permeability test, on the premise that the density and fluidity meet the filling requirements, this paper focuses on the influence of the water binder ratio, bentonite content and age on the unconfined compressive strength, and the permeability coefficient of plastic concrete mixture, then the feasibility of GS curing material used in plastic concrete is evaluated.

Materials and methods

1. Test material

The test materials are GS solidified material (GS for short), Inner Mongolia bentonite (NB for short), water and Fujian standard sand (FS for short). In order to simulate the sandy soil layer often encountered by the vertical anti pollution barrier on site, the commercial poorly graded medium sand, namely Fujian standard sand, is selected. The particle size distribution of Fujian standard sand is measured by the screening method, and that of Inner Mongolia bentonite is measured by the Malvin laser particle size analyzer. The test results are shown in Fig. 1.

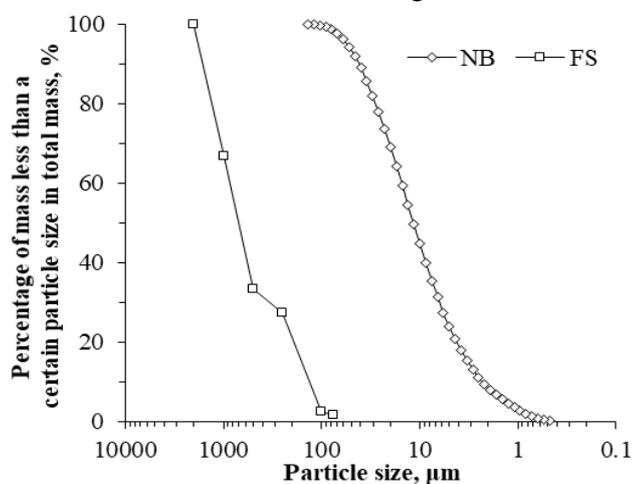


Fig. 1. Particle size grading curve of Fujian standard sand and Inner Mongolia bentonite

The basic physical property indexes of bentonite are determined according to the standards of geotechnical test methods [17], the moisture content is determined by the drying method, the liquid plastic limit is determined by the liquid plastic limit combined tester, and the physical indexes of bentonite are shown in Table 1. The cement used for GS curing material is grade 42.5 ordinary portland cement. The specific surface area of slag micro powder is greater than $0.3 \text{ m}^2 \cdot \text{g}^{-1}$, and the 28 d activity index is greater than 95%. The specific surface area of steel slag micro powder is greater than $0.35 \text{ m}^2 \cdot \text{g}^{-1}$, and the 28 d activity index is greater than 75%.

Table 1

Physical indexes of Inner Mongolia Bentonite

Nature	NB
ω , %	9.06
ω_L , %	113.2
ω_P , %	34.7
I_P	78.5

2. Mix proportion scheme

Referring to the typical example of using plastic concrete mixed materials in the dam repair project [18], and according to the preliminary attempt of this study, the mix proportion is excluded which fluidity does not meet the requirements to ensure that the amount of water and FS remains unchanged. Finally, it is determined that when the NB content is 20%, the water binder ratio is 1.3, 1.5 and 1.7 respectively, when the NB content is 25%, the water binder ratio is 1.5, 1.7 and 1.9 respectively, and

when the NB content is 30%, the water binder ratio is 1.7, 1.9 and 2.1 respectively. A total of 9 sample ratios are shown in Table 2. The age is set at 14 d, 28 d and 60 d, the effects of the water binder ratio, NB content and age on the properties of plastic concrete are studied respectively.

Table 2

Proportioning parameters and main indexes of mixture

Water, $\text{kg}\cdot\text{m}^{-3}$	W/B ratio	NB content, %	FS, $\text{kg}\cdot\text{m}^{-3}$	Fluidity, mm	ρ , $\text{g}\cdot\text{cm}^{-3}$	Curing age, d
400	1.3	20	1200	164.5	2.03	14-28(60)
400	1.5	20	1200	194.0	2.02	
400	1.7	20	1200	218.6	2.03	
400	1.5	25	1200	156.5	2.00	
400	1.7	25	1200	183.5	2.01	
400	1.9	25	1200	199.5	2.01	
400	1.7	30	1200	154.5	2.00	
400	1.9	30	1200	170.0	2.00	
400	2.1	30	1200	187.5	2.00	

Notes: W/B ratio is the ratio of the mass of water to the total mass of GS and NB. NB content is the ratio of NB mass to the total mass of GS and NB.

3. Test method

- Fluidity test

The test method of liquidity refers to the method used by Wu et al. [19], and the liquidity value is used as the evaluation index of liquidity. Firstly, place the fluidity plate horizontally on the ground, smear a layer of vaseline on the inner side of the fluidity cylinder, and then fix the fluidity cylinder in the center of the plate; then pour the mixed suspension into the fluidity cylinder. When the suspension is poured into the fluidity cylinder until it overflows slightly, scrape the overflow suspension with a scraper to make the height of the suspension in the cylinder flush with the height of the cylinder, and then wipe the suspension dripping on the fluidity plate with a dry cloth; then lift the cylinder up slowly. After the suspension diffuses stably around, read out the four values on the scale, add them and divide them by 2 to obtain the fluidity.

- Strength test

The unconfined compressive strength test is carried out by an unconfined compression instrument, and the loading rate is $1 \text{ mm}\cdot\text{min}^{-1}$. The sample size is a cylinder with a diameter of 3.91 cm and a height of 8 cm. Considering that it is difficult to control the height of the sample directly with a mold with an inner diameter of 3.91 cm and a height of 8 cm due to human factors, wrap a circle of transparent tape on the upper part of the mold to make the filling height of the sample slightly higher than 8 cm. When the mold is removed after curing for 2 days, scrape off the excess plastic concrete material with a scraper to ensure that the size of the sample meets the requirements of the geotechnical test method standard. Put the demoulded sample into a constant temperature curing box with a temperature of $20\pm 2 \text{ }^\circ\text{C}$ and a relative humidity of no less than 95%, cure it to the design age (14 days, 28 days and 60 days), and conduct the unconfined compressive strength test.

- Penetration test

According to ASTM D5084 [20], the penetration test is carried out by using the improved flexible wall permeameter. The improved flexible wall permeameter opens a small hole of 3 mm [21] on the sample cylinder, and the spiral groove is engraved inside the sample cylinder to ensure that the confining pressure can be evenly applied to the side wall of the sample through the sample cylinder, as shown in Fig. 2.

Different from other scholars' methods of studying the change of the permeability coefficient with age, considering that plastic concrete materials may begin to penetrate after filling, the test sample is directly filled in the sample cylinder with a rubber membrane for curing. After 3 days, the sample changes from flow plastic state to hard plastic state, osmotic pressure is applied, the penetration test is carried out, and the penetration data are recorded every day. The whole process of the permeability

coefficient changing with age was studied. The permeate adopts laboratory tap water, the confining pressure is set to 100 kPa, the hydraulic gradient is set to 50, and the initial diameter of the sample is 7 cm and the height is 4 cm.



Fig. 2. Modified flexible-wall permeameter

Results and discussion

1. Fluidity

It can be seen from Fig.3 that when the NB content is constant, the fluidity gradually increases with the increase of the water binder ratio, and when the water binder ratio is constant, the fluidity gradually decreases with the increase of the NB content. The preliminary test shows that when the content of NB is 10% and 15%, the water binder ratio changed from 1.3 to 2.3 (variation interval: 0.2), the fluidity is large, and certain bleeding and segregation phenomena are found during the fluidity test; when the NB content is 20%, the water binder ratio is between 1.3-1.7, which can meet the construction workability requirements; when the NB content is 25%, the water binder ratio is between 1.5-1.9, which can meet the construction workability requirements; when the NB content reaches 30%, only the water binder ratio is controlled between 1.7-2.1 in order to ensure good fluidity of plastic concrete and meet the requirements of construction and workability. Therefore, on the premise of meeting the construction workability, the water binder ratio and NB content are selected for the permeability and strength test, as shown in Table 2.

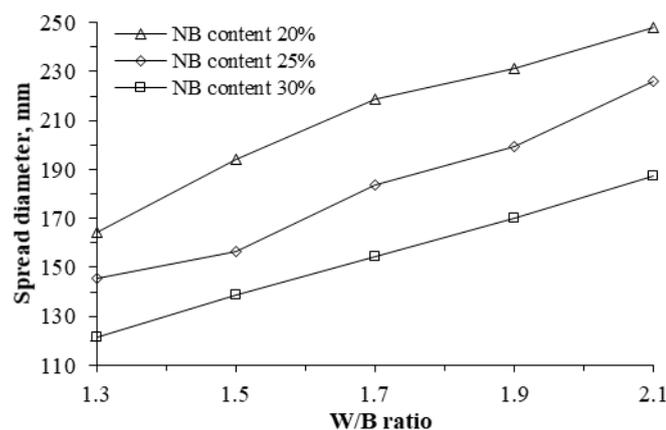


Fig. 3. Fluidity test results

2. Unconfined compressive strength

Fig. 4-6 show the change of the unconfined compressive strength with the water binder ratio and NB content at the age of 14 d, 28 d and 60 d respectively. The following will analyze the impact on the unconfined compressive strength from three aspects: water binder ratio, NB content and age.

At the same NB content and age, the unconfined compressive strength of the sample increases gradually with the decrease of the water binder ratio. Although the unconfined compressive strength of the samples is increasing, the increase of each group is different. According to the different content of NB, the variation law of unconfined compressive strength with water binder ratio is divided into two cases: one is that the content of NB is 20%, the other is that the content of NB is 25% and 30%. When the content of NB is 20%, with the decrease of the water binder ratio, the unconfined compressive strength at each age continues to increase and increases greatly. The increases at 14, 28 and 60 days are 77.5%, 78.4% and 100.4% respectively. When the NB content is 25% and 30%, the unconfined compressive strength at each age increases with the decrease of the water binder ratio. However, different from the NB content of 20%, when the NB content is 25% and 30%, the unconfined compressive strength increases greatly at the age of 14 days, 70.9% and 111.5% respectively, while at the age of 28 days and 60 days the unconfined compressive strength increases slightly, ranging from 25.1% to 53.3%.

Under the same water binder ratio and age, the unconfined compressive strength decreases with the increase of the NB content. When the water binder ratio was 1.5 and the content of NB increased from 20% to 25%, the unconfined compressive strength decreased significantly at each age, ranging from 16.9% to 22.7%; When the water binder ratio is greater than 1.5, with the increase of the NB content, the reduction rate of the unconfined compressive strength at each age slows down and the decrease amplitude decreases, ranging from 2.8% to 11.7%. Compared with the change of the water binder ratio, the content of NB has little effect on the unconfined compressive strength of the sample [22].

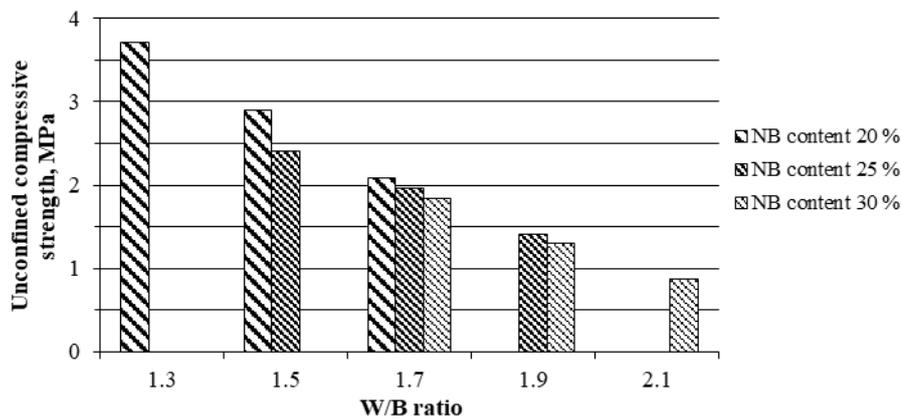


Fig. 4. Unconfined compressive strength at 14 days of age

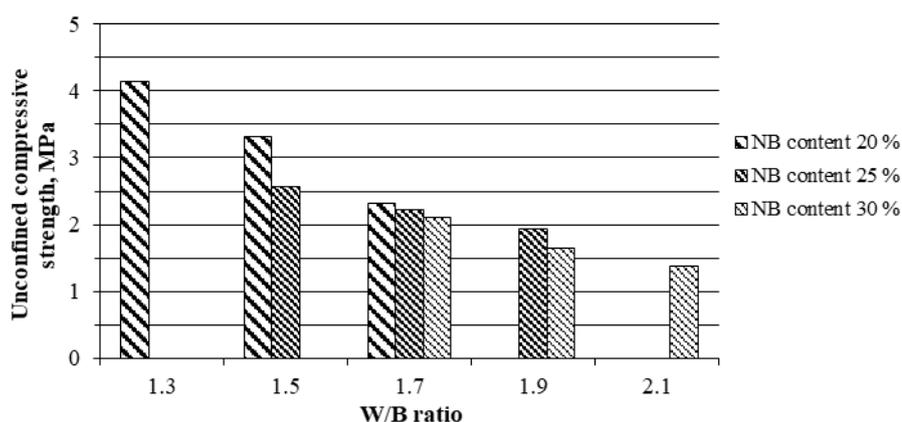


Fig. 5. Unconfined compressive strength at 28 days of age

With the increase of the age, the unconfined compressive strength of the samples with 9 ratios gradually increases, but not all ratios meet the engineering strength requirements with a strength greater than 2 MPa at the age of 28 days. When the water binder ratio is in the range of 1.3-1.7, even if the content of NB increases to 30%, the strength of each ratio sample meets the requirements, and the unconfined compressive strength at 28 days can reach 4.14 MPa; when the water binder ratio is 1.9, the

28 d strength of each ratio does not meet the engineering requirements. If the water binder ratio continues to increase, the unconfined compressive strength will not reach 2 MPa even at the age of 60 days.

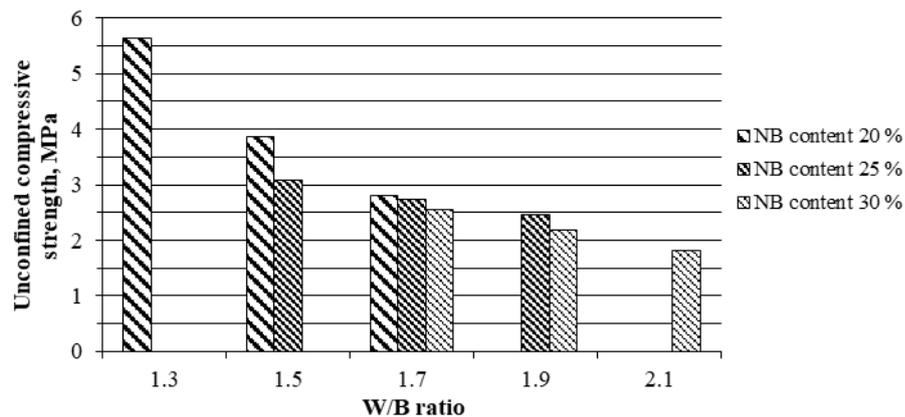


Fig. 6. Unconfined compressive strength at 60 days of age

The reason for the continuous growth of plastic concrete strength is that the content of active components such as slag, steel slag and fly ash is much lower than that of Portland cement. In alkaline environment, slag, steel slag and fly ash can react [23; 24]. The early strength is mainly provided by cement hydration reaction. Cement hydration generates calcium hydroxide. The pH of its saturated solution is between 12-13, which is strongly alkaline. Slag, steel slag hydration reaction and pozzolanic reaction of fly ash in alkaline environment continue to increase the later strength of plastic concrete. The reason why the change of the NB content has little effect on the strength of plastic concrete is that bentonite has strong water absorption and will produce plasticization after encountering water, resulting in the reduction of the strength of plastic concrete. However, a small amount of active silica and active alumina in the soil will combine with cement hydration products to produce new hydration products, which improves the curing capacity of cement soil system [25], to some extent, the reduction of strength is inhibited.

3. Permeability

Fig.7-9 show the change of the permeability coefficient with the water binder ratio and age under different NB content, and Fig.10 shows the change of the permeability coefficient with the NB content and age when the water binder ratio is 1.7. The following will analyze the influence on the permeability coefficient from three aspects: water binder ratio, NB content and age.

It can be seen from Fig.7-9 that under the same NB content and age, the permeability coefficient gradually decreases with the decrease of the water binder ratio. Although the permeability coefficient is decreasing, the reduction of each group is different. According to the content of NB, the variation law of permeability coefficient with water binder ratio is divided into two cases: one is that the content of NB is 20%, the other is that the content of NB is 25% and 30%. When the content of NB is 20%, the permeability coefficient at each age decreases with the decrease of the water binder ratio, but the decrease range is small, which is basically no more than one order of magnitude; when the NB content is 25% and 30%, the permeability coefficient changes greatly with the decrease of the water binder ratio. When the water binder ratio is greater than or equal to 1.9, the permeability coefficient cannot reach the order of $10^{-7} \text{ cm}\cdot\text{s}^{-1}$. When the water binder ratio is reduced from 1.9 to 1.7, the permeability coefficient decreases rapidly, even reaching the order of $10^{-8} \text{ cm}\cdot\text{s}^{-1}$.

It can be seen from Fig.10 that under the same water binder ratio and age, the permeability coefficient decreases with the increase of the NB content. When the age is less than 16 days, the content of NB has a great influence on the permeability coefficient. Taking 14 days as an example, the content of NB increases from 20% to 30%, and the permeability coefficient increases from $2.59 \times 10^{-6} \text{ cm}\cdot\text{s}^{-1}$ reduced to $1.73 \times 10^{-7} \text{ cm}\cdot\text{s}^{-1}$, the decrease range is 93.3%, but with the increase of the age, the influence of the NB content on the permeability coefficient gradually decreases. When the age reaches 28 days, the NB content increases from 20% to 30%, and the permeability coefficient increases from $3.47 \times 10^{-8} \text{ cm}\cdot\text{s}^{-1}$ reduced to $2.41 \times 10^{-8} \text{ cm}\cdot\text{s}^{-1}$, with a reduction of only 30.5%. In general, with the increase of the age, the effect of the NB content on the permeability coefficient becomes smaller and smaller.

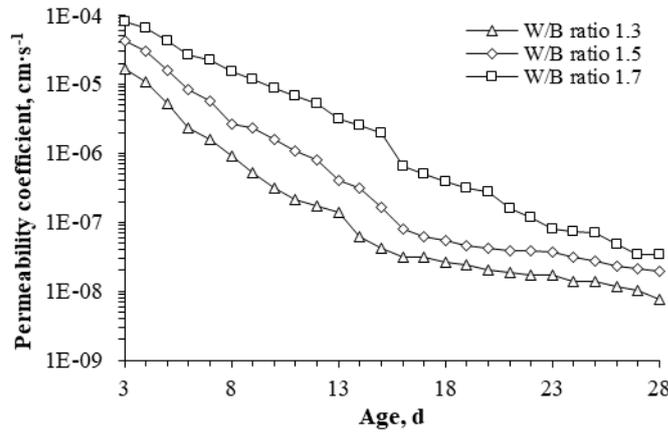


Fig.7. Variation curve of permeability coefficient with W/B ratio and age when NB content is 20%

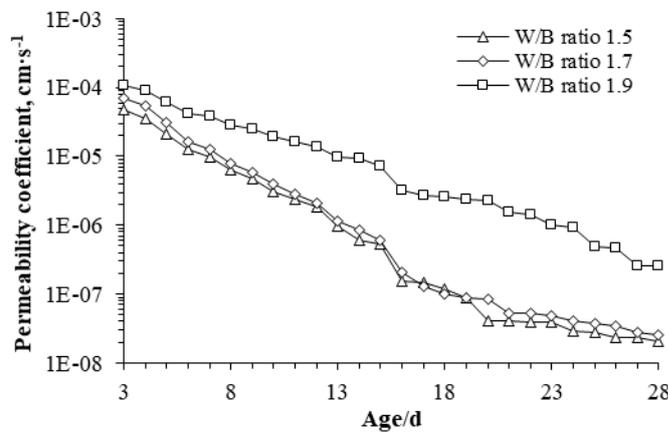


Fig. 8. Variation curve of permeability coefficient with W/B ratio and age when NB content is 25%

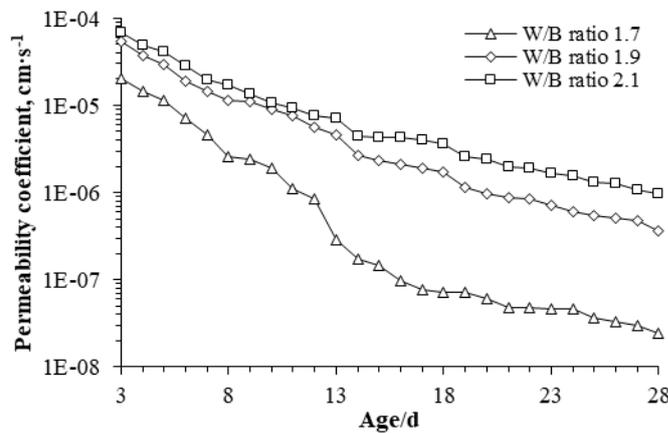


Fig. 9. Variation curve of permeability coefficient with W/B ratio and age when NB content is 30%

When the water binder ratio is between 1.3 and 1.7, the variation law of permeability coefficient with age is obvious. The permeability coefficient decreases rapidly and greatly from 3 days to 13 days. There is an inflection point in the decreasing trend of the permeability coefficient from 13 days to 18 days. When the age is greater than 18 days, the decreasing rate of the permeability coefficient slows down and gradually tends to be flat. When the water binder ratio is between 1.9 and 2.1, the permeability coefficient decreases gradually with age. Although there is no obvious inflection point, the overall

change law is consistent with the above law. The permeability coefficient decreases rapidly in the early stage and slows down in the later stage.

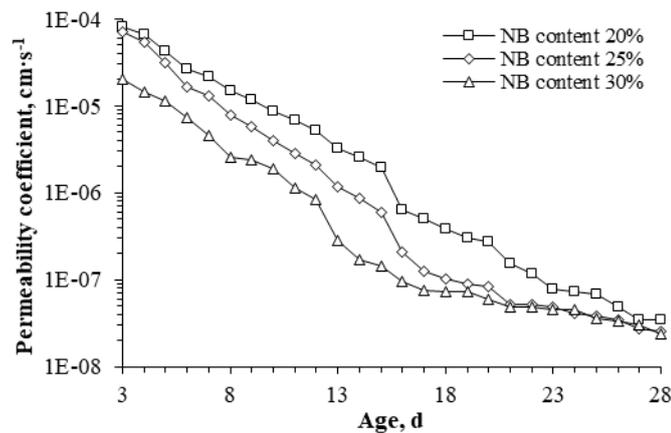


Fig. 10. Variation curve of permeability coefficient with NB content and age when W/B ratio is 1.7

The micro pores in plastic concrete are the main cause of water seepage. The cement hydration products fill and block the pores, resulting in a rapid decline in the permeability coefficient. However, the cement accounts for a small proportion in the GS solidified materials, mainly slag, steel slag and fly ash. These three materials have few active components and need to react in an alkaline environment. With the extension of the penetration time, the hydration reaction and pozzolanic reaction of the three materials make the plastic concrete more dense, resulting in the further reduction of the permeability coefficient. Bentonite particles can block most of the voids between cement particles and their hydration products. At the same time, bentonite particles can adsorb a large number of water molecules through the action of positive and negative charges, so that most free water molecules in plastic concrete can be changed into combined water molecules, reducing the water seepage area, which is conducive to the reduction of the permeability coefficient.

Conclusions

Based on the fluidity test, unconfined compressive strength test and improved flexible wall permeability test, this paper studies the basic properties of GS solidified material instead of cement to prepare plastic concrete. The main conclusions are as follows.

1. The fluidity increases with the increase of the water binder ratio and decreases with the increase of the bentonite content. In order to meet the construction and workability requirements, when the bentonite content increases, the water binder ratio increases accordingly. Similarly, when the water binder ratio decreases, the bentonite content decreases accordingly.
2. With the increase of the bentonite content, the unconfined compressive strength decreases, but the decline is not obvious; with the decrease of the water binder ratio or the increase of the age, the unconfined compressive strength increases. At the age of 14 days, the growth range is large, with the growth range of 70.9-111.5%. At the age of 28 days and 60 days, the growth range decreases with the increase of the bentonite content.
3. With the increase of the bentonite content, the variation range of the permeability coefficient in the early stage is large, and the variation range decreases in the later stage, from 93.3% to 30.5%; with the decrease of the water binder ratio, the permeability coefficient decreases. When the water binder ratio decreases from 1.9 to 1.7, the permeability coefficient is greatly improved, from less than $10^{-7} \text{ cm}\cdot\text{s}^{-1}$ to $10^{-8} \text{ cm}\cdot\text{s}^{-1}$.
4. When the water binder ratio is between 1.3 and 1.7, the permeability coefficient has an inflection point between 13 and 18 days. Before that, the permeability coefficient decreases rapidly, and then tends to be flat. When the water binder ratio is between 1.9 and 2.1, the permeability coefficient decreases gradually with the increase of the age, and there is no inflection point.

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Author contributions:

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