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A Study on Different Dosage of the Cement, Lime and Gypsum Curing Recycled Concrete Debris

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The process of research on the compressive strength, the porosity and mechanism of solidifying concrete debris relationship with the dosage of the cement, lime and gypsum is explained based on the filling and cementating theory. According to the research, the dosage of cement curing agent used for cementing and filling the pores among the grains of concrete debris is consistent with that of compressive strength and porosity from different methods of curing concrete debris. However, the dosage of lime and gypsum curing agent are not the case. That is to say, the dosage of cement used for filling and cementing pores in experiment is equal to that from the theory. But the dosage of lime or gypsum from the experiment is less than that of fully filling the pores among concrete debris from theoretical calculation. It is demonstrated that the process of cement solidifying concrete debris complies with the theoretical model of stabilized soil, while the cement-lime or cement-gypsum composite solidifying agent does not. A hypothesis is made that the mechanism of cement solidifing debris is achieved through filling and cementing. Based on microstructure analysis, a conclusion would be made that the mechanism of the curing agent made by cement - lime or cement - gypsum composite is that their interactions produced a large amount of acicular ettringite and gelling materials, and the interaction of these sediment particles is able to improve the microstructure of solidified objects. For this reason, macroscopic compr essive strength of curing concrete debris was improved.

1. Introduction

The strength of the concrete debris solidified by cementatory solidifying agent can be divided into the strength of the debris grains, the strength from the cementation of solidifying agent being hydrated and hardened, the strength results from pozzolanic reaction and the strength generated by filling pores. According to the references (Gartner and Hirao, 2015), the strength of solidified concrete debris mainly depends on the cementation of solidifying agent being hydrated and hardened and the filled pores effect (Mymrin et al., 2015). However, a large amount of cement would be needed to solidify the concrete debris because the cementatious substance produced by the hydrated cement mainly plays the role of cementing the poses among concrete debris (Lopez-Uceda et al., 2016). For the reason, if the cement is used as curing agent, a large amount of cement would be needed to form a reinforced solidified body, otherwise, the effects of the solidifying concrete debris would not be better because of the pores among the concrete debris. The cost would be much higher if the dosage of cement is increased although the effect of solidifying concrete debris would be improved (Jayakody et al., 2014). Moreover, the reason of cement, lime and gypsum dosage difference is not clear (Pasandín and Pérez, 2015). To solve the problems, a certain amount of lime or gypsum is added into the cementatory solidifying agent. They would not only improve the strength of solidified concrete debris but also lower the cost (Letelier et al., 2017). The application effect of cement and lime, cement and gypsum solidifying concrete debris and their acting mechanisms have not been reported (Samiei et al., 2015). For this purpose, the solidified soil accumulation theory model is quoted in this paper. According to the theory of accumulation model, the concrete debris solidified would be taken by experiments to determine the strength of concrete debris solidified by cement related to the dosage (Limbachiya et al., 2012). The ratios of lime and gypsum in the cement-lime and cement-gypsum complex solidifying agent would be

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determined by the results of compressive strength experiments. The calculated porosity, and porosity of the solidified concrete residue samples by mercury intrusion method tested (i.e. cement group, cement-lime group and cement-gypsum group) are compared. The micro porosity analysis would be made for the samples with their respective curing agent dosages so as to probe the relation between the macro properties and micro structures of the solidified concrete debris. The difference in the functional mechanism between cement and cement-lime and cement-gypsum are probed. Three groups of samples would be prepared for the experiment, as are shown in Table 1.

Table 1 Theoretical calculations of the parameters of the stabilized debris

Group name	η1							ρ	W1	W2	e 90
	1.8	1	0.88	0.6	0.425	0.35	0. 25				
Cement group	22.2	19.2	17.8	15.1	13.1	10.8	2.3	75.4	11.7	11.3	16.6
Lime group	22.2	19.2	17.8	15.1	13.1	10.8	2.3	75.4	11.7	12.1	12.9
Gypsum group	22.2	19.2	17.8	15.1	13.1	10.8	2.3	70.5	11.7	12.4	8.1

2. Theoretical Computing

Formula Derivation

Solidifying concrete debris with cement is defined as that the concrete debris proposed to be solidified are mixed uniformly with some cement by a certain method, and the concrete debris are recycled and not harmful to the environment. In accordance with the theory, the reason why the strength of concrete debris being solidified by cement is so high is that the cement grout encased, adglutinated the grains and filled their pores. The quantities of the cement used for encasing and adglutinating the concrete debris and filling their pores can be calculated specifically. Suppose that the quantities of cement used as encasing and adglutinating the grains of concrete debris is W1, and the quantities used as filling the pores among the concrete debris is W2. The content of cement can be denoted by the mass percentage of the cement to the mixture (cement+concrete debris). Thereby the quantities (W1 and W2) of the cement used for encasing and filling the debris fully can be calculated as follows:

$$W_1 = \frac{W_{1cement}}{W_{1cement} + W_{1debris}} = \frac{V_m \rho_m}{V_m \rho_m + (1+\mu) G_s V_s} \tag{1}$$

$$W_2 = \frac{W_{2mass-filling-grout} - W_{2mass-water-filling-grouts}}{W_{2mass-debris} + W_{2mass-filling-grout} - W_{2mass-water-filling-grouts}} = \frac{(1-\rho)\rho_m}{G_s V_s (1+\mu) + (1-\rho)\rho_m} \tag{2}$$

η_i represents the mass percentage of granular diameter group of *i* in concrete debris encased by cement;
d^i represents the mean diameter of the granular diameter group of *i* in the concrete debris;
$\eta_i^{'}$ represents the mass percentage of the granular group of *i* in the concrete debris;
h represents the thickness of grout film；

where ρ represents the bulk density of concrete debris, ρ can be derived according to Stovall bulk density of grains in the ideal spherical grain system.

Porosity Theory

In the case of grouts fully encasing the concrete debris and fully filling the pores in the grain system of the concrete debris, and in the premise of the cement being completely hydrated and of the same volume during hydrating in 90d curing age, the porosity e_{90} of the solidified concrete debris by cement in 90d curing age can be calculated from the formula as follows:

$$e_{90} = [1 - \frac{kV_c \rho_m}{1+\mu}] V_m \rho + (1-\rho)[1 - \frac{k\rho_m V_c}{(1+\mu)}] \tag{3}$$

[3]

Where *k* represents the volume expansion coefficient of solid phase after the reaction of curing agent, and the volume expansion coefficient of hydrated cement is 2.06; the volume expansion coefficient of the hydrated gypsum is 2.5; the volume expansion coefficient of the hydrated lime is 2.2. V_c represents the absolute volume of cement with unit mass, and it is usually 0.319 cm3/g.

Computing Results

In accordance with the experiment, the value of μ is 0.5, and the density of cement grout ρ_m equals to 1.68 g/cm3, and the density of gypsum grout is 1.50g/cm3, and Gs equals to 2.22 g/cm3. According to the research made, suppose the thickness of cement grout film on the surface of the grains of the debris in the mixture is 23μm, the bulk density of the concrete debris system in which the solidified concrete debris is fully encased by cement grout, and the contents W_1 and W_2 corresponds respectively to concrete debris being fully encased by grout and grout fully filling the pores among the concrete debris, and the porosity of the stabilized concrete debris at 90d curing age based on the derived result.

3. Materials

The experiment materials include Dian'e brand P.S 32.5(a kind of Chinese registered brand) slag portland cement, lime, gypsum, tap water in Kunming city, the concrete debris (their particles size is smaller than 4.75mm). In order to obtain the effects with different solidifying agents on solidifying concrete debris, three groups experiment materials designed as shown in the Table 1. As water-cement ratio was 0.5, the mixtures were uniformly mixed. Three groups of experiments are designed according to the principle of curing. The test ratios and the compositions are shown in the Table 1. A certain amount lime and gypsum are added in the second and the third group respectively with adding 12.5% cement in their groups. The experimental samples are made according to the Test procedures for the stability of inorganic materials in highway engineering JTJ057-94. Mercury intrusion method can be used to measure the porosity of the solidified concrete debris. The solidified concrete debris, which is curing to 90d, would be soaked with anhydrous ethanol to stop their hydration for one day, then dry them to constant weight at 85 °C temperature and measure them. The model of the mercury intrusion device is mMK-AutoPore IV9500. In detail, choose a representative SEM image to magnify for 1000 times to make image analysis respectively. The image resolution is 0.095 $\mu m \cdot pixel^{-1}$ and the analysis regions are identical (127.8μm×95.8μm). The IPP professional image processing software are used to process image, and make measurements and statistics for the sizes, areas and numbers of the pores in the images. The Statistical and measuremental datas are shown in the Table 2.

Table 2: Contrast of theoretical calculations with experimental results

Group name	Test results/%			Theoretical calculation results /%		
	W1 t	W2 t	e90 t	W1	W2	e90
Cement group	11	11	16.6	11.7	11.3	17.2
Lime group	11	3.5	12.3	11.7	12.1	13.1
Gypsum group	11	3.5	11.1	11.7	12.4	10.4

The strength of the concrete debris only solidified by the cement at 90d curing age increases with the amount of cement(w), as shown in Figure1. The strength is denoted by q_w. It can be clearly seen that the strength of the solidified concrete debris increases significantly with the cement contents. Suppose the cement content incr easing from w-2 to w, the increment of the strength of the solidified concrete debris is Δq_w, then $\Delta q_w = q_w - q_{w-2}$ (w=4 , 6……24 , 26)

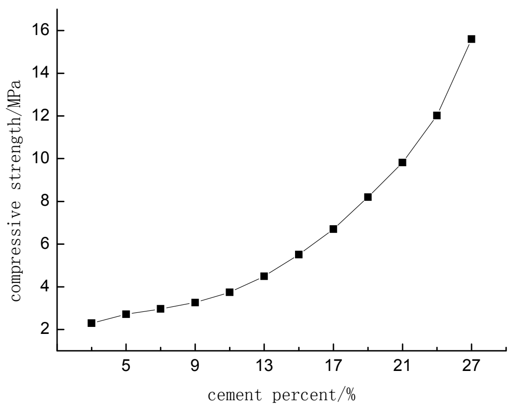

Figure 1: Relationship between compressive strength of the stabilized debris and cement content.

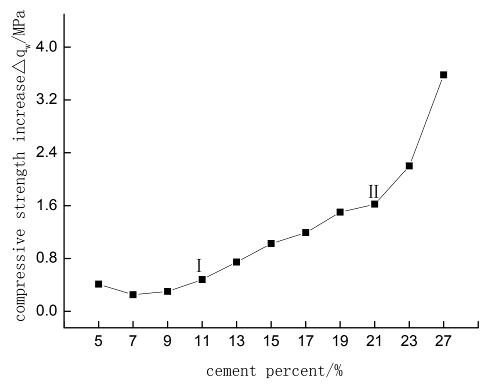

Figure 2: The relationship between the strength in cement of the stabilized debris and cement content

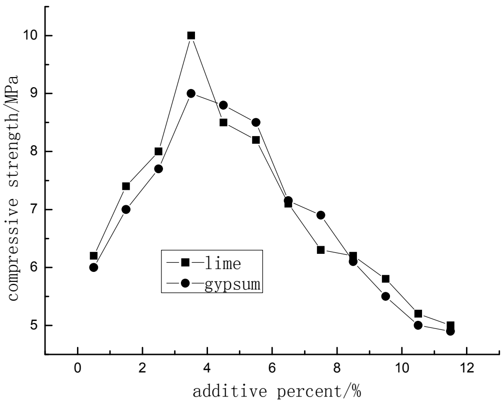

Figure 3: Relationship between compressive strength inof the stabilized debris and loading agent content. content.

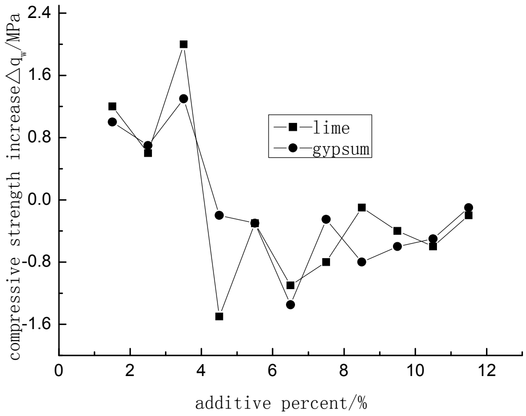

Figure 4: Relationship between compressive strength cement of stabilized debris and loading agent

The Figure 1~Fig.4 have been had according to the compressive strength experiment data. it can be seen that strength variation can be divided into three sections, Their turning points are denoted as I and II respectively, which represent the cement percentage 12% and 25%. The difference between I and II is 13%, which is the difference from cement contents of concrete debris between the two points.

4. Comparative Analysis

From the cement contents calculated on theory corresponding to each point of inflexion shown in Figure 2, it can be seen that the experiment results correspond to the concrete debris fully encased by cement grout calculated on theory. During the process of strength increment of solidified concrete debris, the cement content when the pores is fully filled with grout corresponded to the value 25.4% calculated on theory is basically the same as that value 25% from the experiment. The porosity (17.2%) calculated on theory of stabilized debris at 90d curing at age is almost consistent with the experiment result (16.6%) measured by mercury injection methods and statistic porosity (16.5%) with SEM methods (see Table 3).

Table 3: The pores parameters of solidified mass samples with stabilized debris

Name	Pore chara cteristics	Pore level							
		1	2	3	4	5	6	7	8
Cement group	number	159	24	14	7	5	3	2	2
	size μm	1.427	3.445	4.321	7.641	9.631	10.276	14.791	17. 312
	area μm2	1.52	9.75	12.53	23.89	32.96	86.54	120.57	270.12
Lime group	number	230	31	14	7	6	3	1	1
	size μm	1.320	3.055	4.021	5. 174	7. 325	8. 902	12.735	15.142
	area μm2	1.43	9.64	11.74	21.21	30.44	59.43	120.56	176.08
Gypsum group	number	250	30	12	3	3	1	1	0
	size μm	1.206	2.800	3.636	5. 075	6.886	8.213	10.687	
	area μm2	1.4	8.54	7.24	18.4	27.34	35.42	110.35	

While the lime and gypsum required by fully filling the pores among the debris with grouts on theory are 12.1% and 12.4% respectively, which are much different from those experiment value when the strength of the stabilized debris reachs the peaks (as shown in Fig.3). Namely, the ratios of the lime or gypsum used to fill the pores of the debris in experiment are far fewer than those calculated on theoretical analysis, the strength property of the debris stabilized with lime or gypsum is almost the same as that of the debris stabilized with cement fully filling the pores. It shows that the specific strength of the group of cement serving as filler is a bit higher than that of the other two groups, but the porosity is inferior to that of stabilized debris only filled with 4% lime or with 4% gypsum. It can be seen that the formation theory of debris solidified by cement could explain the reason why the cement solidifying concrete debris comply with the formation theory of stabilized debris structure. The experiment results show that the theory on the formation of stabilized debris structure fails to explain the formation of the composite solidifying agent composed of more than one kind of materials. The reason may be: when only the cement solidifying agent is used, the cement plays the same role during the formation of solidified debris within the scope of the quantities of cement. While the debris mixed with the cement, the grouts encased the surface of the debris and the cementing materials produced by the hydration of cement are mainly used to adglutinate the debris. So the compressive strength of the solidified debris linearly depends on the cement contents (Figure1) and shows obvious regularity. When the concrete debris is mixed with grouts, the grains of the debris are encased by the grouts. Within the cementing materials produced by the hydration of the cement, some of them are used to adglutinate hydrated calcium silicate of the debris grains, the others have a chemical reaction with lime or gypsum. Therefore the compressive strength of the solidified debris not only depends on the adglutinated number of points and the adglutinated degree of the debris grains, but also is affected by the structure and state of the produced materials of the chemical material (Figure 5a, Figure 5b).

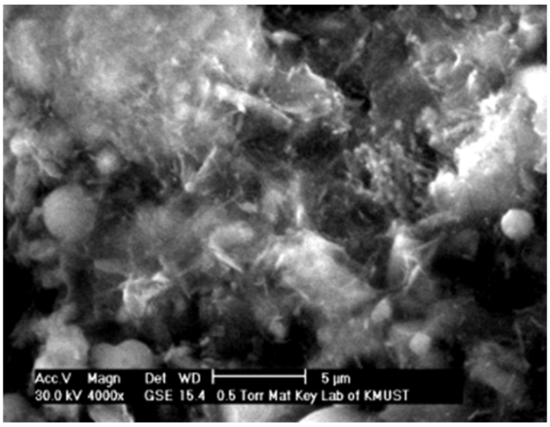

Figure 5a: The SEM of solidified building residues by 12% cement and 2% lime at 90d age

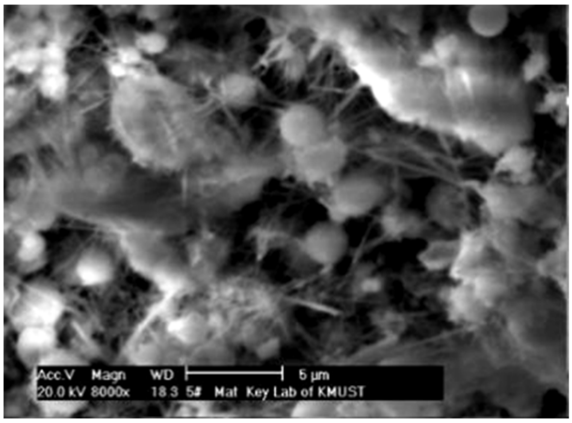

Figure 5b: The SEM of solidified building residues by 12% cement and 2% gypsum at 90d age

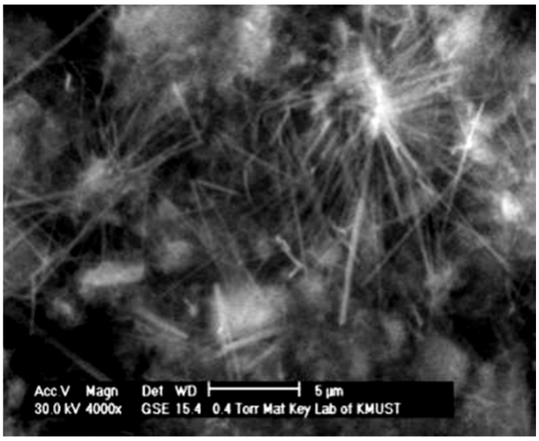

Figure 5c: The SEM of solidified building residues 12% by 12% cement and 4% lime at 90d age

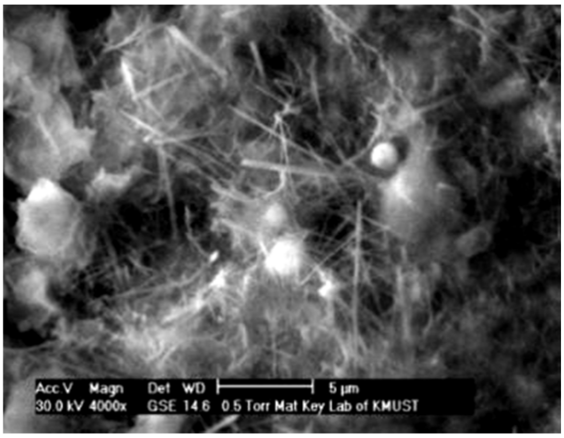

Figure 5d: The SEM of solidified building residue s by cement and 4% gypsum at 90d age

And the effects of the mixtures are better than those of the entire cement. For the solidified debris with lime or gypsum, with the increment of the amount of lime or gypsum, the compressive strength of the solidified debris experiences three stages: increasing slowly, increasing sharply to reach a peak and decreasing. As the amount of lime or gypsum is increased, due to the excessive lime or gypsum decreases the internal frictional coefficient and cohesion of the solidified debris, the compressive strength of the stabilized debris would be decreased. So there is an optimum for the ratio of lime or gypsum in the solidified debris with cement. In the case of the optimal amount of lime or gypsum being added, the volume of acicular ettringite increases very large during its formation and fully fills the pores among the solidified debris. Furthermore, the acicular and columnar crystals intercrossed in the pores of the stabilized debris to form a three-dimensional spatial structure with the hydrated calcium silicates (Figure 5c , Figure 5d) . They play a role of supporting and making the strength of the stabilized debris increased. What is more, the acicular ettringites are formed to make the pores in the alite shrink and move, which changes the micro structure of the pores in the alite.

5. Conclusion

(1) The dosage cement used to cure the concrete debris and fill the pores among the concrete debris can be determined by experiments during the formation of the solidified concrete debris. The cement solidifying concrete debris complies with the theoretical model of solidified soil. It concludes that solidifying concrete debris with cement-lime or cement-gypsum composite solidifying agent does not comply with the hypothesis of the theoretical model on the structure of solidified soil.

(2)The mechanism of lime or gypsum solidified concrete debris is that the cement takes chemical reaction with the lime or gypsum to produce a new substance–acicular ettringites, which is different from the lime or gypsum itself in micro-structures and fill parts of the pores among the solidified concrete debris on the one hand, for the volume of them is expended very large during their formation. On the other hand, their acicular, needle-like or columnar crystals intersected mutually in the pores to form interlaced spatial structures with calcium silicate hydrate. These crystals play the role in supporting pores, reducing or diminishing the mean aperture among the solidified debris. Which improves compressive strength of the solidified concrete debris.

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