Effect of adding waste boulder powder on mechanical properties of green concrete

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Abstract. Reusing of stone powder formed in the production of manufactured sand is of great significance to environmental protection and resource utilization. In this paper, C30 and C40 environment-friendly manufactured sand concrete were prepared by adding 6%, 9%, 12% and 15% of waste boulder powder from manufactured sand production line into concrete and controlling the total weight of manufactured sand and rock powder to be constant. The influence of stone powder on concrete fluidity, compressive strength and elastic modulus were analysed. It was found that with the increase of stone powder content, the compressive strength of fresh paste and C30 concrete first increased and then decreased, while the elastic modulus of concrete and the compressive strength of C40 concrete continued to decrease. It is suggested that the content of rock powder should not exceed 9%.

1 Introduction

With the increase in the scale of national infrastructure construction and the advancement of the "One Belt One Road" initiative, concrete raw materials, especially mineral admixtures, are in short supply in many regions. Fraud and adulteration of mineral admixtures (granulated blast furnace slag powder, fly ash, silicon ash, etc.) often occur, which greatly affects the quality of engineering construction. At present, many scholars are devoted to the research of new supplementary cementitious materials, such as limestone powder [1–4], metakaolin [5–9] and steel slag powder [10–13], to cope with current shortage of traditional mineral admixtures.

Phnom Penh-Sihanoukville Expressway (PPSE) is an important golden channel connecting Phnom Penh, the capital of Cambodia, to Sihanouk, the largest seaport in China and an external port. The construction of PPSE is of great significance for promoting the local economic development of Cambodia and implementing the "One Belt One Road" initiative. The starting point of PPSE is at the intersection of National Highway No. 4 and Phnom Penh City Circle Line in Cambodia, and the end point is on the No. 4 road on the edge of Sihanoukville. It is about 8.6km away from Sihanoukville Port to the west and about 5.5km away from Westport Economy, and it is about 8.5km from Sihanoukville Airport. The total length is 187.05Km. The whole line adopts Chinese highway construction standards and specifications. The design speed is 100Km/h, and the two-way four-lane.

The construction of PPSE also faces the problem of the lack of high-quality mineral admixtures and river sand resources. The project adopts the common boulder production manufactured sand along the project, and a large amount of rock powder of boulder is produced during the production process. If the boulder powder is recycled as mineral admixtures in engineering concrete production through research, not only could the pollution of the environment by the stacking of stone powder be solved, but also ordinary mineral admixtures could be replaced, and construction costs could be reduced. Hence, this paper studies the influence of different content of boulder powder on mechanical performance of concrete with different water-to-binder ratio and provides basic research data support for the application of boulder powder in engineering.

2 Material and testing method

2.1 Raw material

The apparent density of manufactured sand is 2650 kg/ m^3, the loose bulk density is 1630 kg/m^3, the porosity of loose bulk is 41%, the content of stone powder is 10.2%, the fineness modulus is 2.94, the water demand ratio is 103%, the MB value is 0.75, and the maximum crushing index of single stage is 16.5%. The crushed stone used is composed of 5-10 mm, 10-20 mm and 31.5 mm graded crushed stone with mass ratio of 2:5:3. The content of needle flake particles is 0.6%, and the maximum crushing index of single stage is 8.7%.

The waste boulder powder was collected from the limestone manufactured sand production line and screened by 0.075mm screen. The test results showed that the fluidity ratio was 106%, the water demand ratio was 98.30%, the MB value was 3.8, the specific surface area was 900.21 kg/ m^3, the density was 2655 kg/ m^3, the water content was 0.41%, and the 7d activity index was 90%. Using P.O. 42.5 cement, standard consistency

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27.1%, specific surface area 326m^2/kg, initial setting time 161min, final setting time 246min, 3d strength 32.2MPa, 28d strength 57.5MPa. Type F class II fly ash is used, with fineness of 13.2% (45μm sieve residue) and 28d activity index of 74%. Using polycarboxylate water reducer, the solid content is 30.2%, and the water reducing rate is 28%.

2.2 Mix proportion

The influence of waste boulder powder on the performance of manufactured sand concrete was shown in Table 1. The water-to-binder ratio (W/B) of 0.44 and 0.38 were designed respectively to prepare C30 and C40 strength grade concrete and compare the influence of W/B. The total weight of manufactured sand and waste boulder powder in C30 was 798 kg/m^3, and that in C40 was 814 kg/m^3. The amount of rock powder in brackets after the weight of rock powder was 6%, 9%, 12% and 15% respectively.

Table 1 Mix proportion of influence of content of waste boulder powder on mechanical properties of concrete (kg/m^3)

Sample ID	Cement	Fly ash	Manufactured sand	Waste boulder powder	Coarse aggregate	Water	W/B
C30-S-6	294	74	750	48 (6%)	1058	162	0.44
C30-S-9	294	74	726	72 (9%)	1058	162	
C30-S-12	294	74	702	96 (12%)	1058	162	
C30-S-15	294	74	678	120 (15%)	1058	162	
C40-S-6	341	85	765	49 (6%)	994	162	0.38
C40-S-9	341	85	741	73 (9%)	994	162	
C40-S-12	341	85	716	98 (12%)	994	162	
C40-S-15	341	85	692	122 (15%)	994	162	

2.3 Testing method

The slump, slump-flow and air content of concrete were tested in accordance with the Chinese standard *Standard for test method of performance on ordinary fresh concrete: GB/T 50080-2016*; The compressive strength and static compressive elastic modulus of hardened concrete (hereinafter referred to as elastic modulus) are tested in accordance with the Chinese standard *Standard for test method of concrete physical and mechanical properties: GB/T 50081-2019*. The size of compressive strength test specimen was 100 mm cube, and the test age was 3d, 7d, 28d and 56d. The test age of elastic modulus was 28d and 56d.

3 Result and discussion

3.1 Workability

Fig. 1 showed the effect of waste boulder powder on the workability of manufactured sand concrete under different W/B and stone powder content.

According to the change of slump, when the stone powder content increased from 6% to 15%, the slump of fresh paste first increases and then decreased. When the stone powder content in C30 concrete exceeded 12%, the slump decreased, and when the stone powder content in C40 concrete exceeded 9%, the slump began to decrease. The relationship between slump, air content and slump-flow of fresh paste were quantitatively described in Fig. 2. In order to characterize the correlation between fresh concrete performance and stone powder content, the quadratic function model was used to regress the relationship between concrete fluidity, air content and stone powder content in Fig. 3. It was found that there was a significant quadratic function relationship between concrete slump, slump-flow, air content and stone powder content under different W/B, which confirmed the rule that the fluidity in Fig. 1 first increases and then decreases.

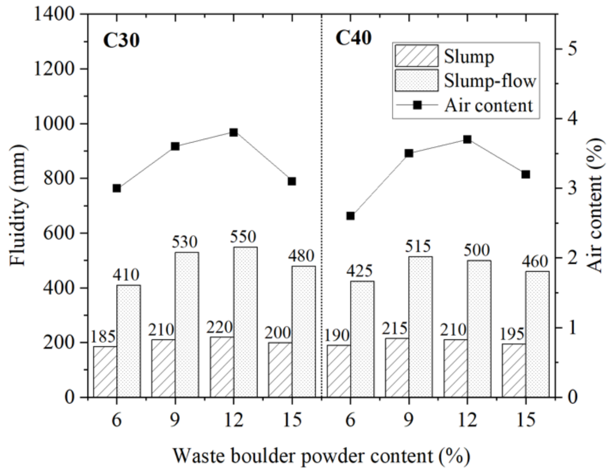

Fig. 1 Effect of waste boulder powder on workability of manufactured sand concrete

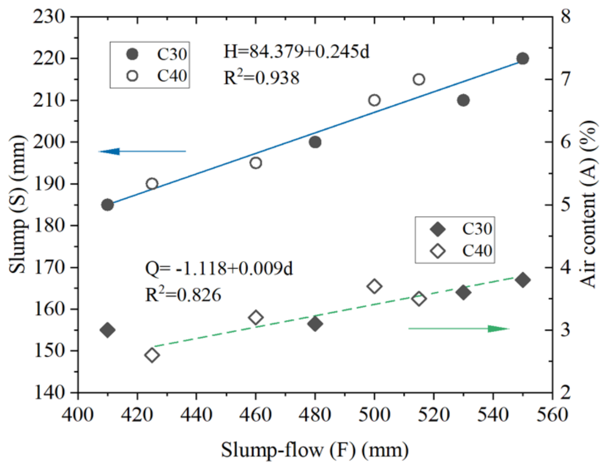

Fig. 2 Correlation of slump, air content and slump-flow of waste boulder powder concrete

As a kind of calcareous powder, the biggest difference between limestone powder and granite, basalt and other rock powder lay in its small adsorption performance. According to the research [14,15], the surface energy of calcium carbonate in limestone powder particles was about 230×10^{-7}J/cm^2. Low surface energy could reduce the water demand ratio of concrete with limestone rock powder, that is, reduce the water absorption of paste or have water reducing effect. Therefore, with the increase of calcareous rock powder content, the fluidity of concrete gradually increased, which was similar to the existing research results [16–18]. However, the MB value of rock powder used in this paper reached 3.8, which reflected that the rock powder contains more clay debris to a certain extent. When the content of stone powder exceeded a certain extent, the strong adsorption impurities absorb a large amount of free water, which weakened the fluidity of the paste. At the same time, the specific surface area of stone powder reaches 900 g/cm^3, and more mixing water is needed to wet the surface of stone powder particles to form a water film, resulting in the decline of concrete workability.

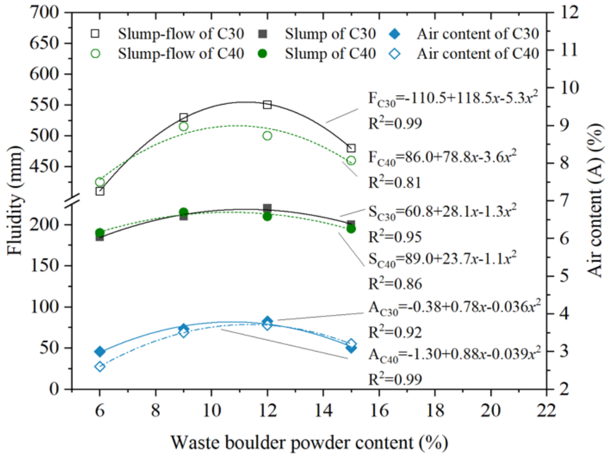

Fig. 3 Correlation between fluidity, air content and stone powder content of waste boulder powder concrete

3.2 Compressive strength

The experimental results of the influence of concrete prepared with waste boulder powder on its strength were shown in Figure 4. The solid line symbol represented C30 concrete, and the dotted line symbol represented C40 concrete.

With the increase of stone powder content, the strength of C30 concrete at different ages first increased and then decreased. The strength of C30-S-9 specimen was the highest at each age, and its 56d strength was 65.5MPa. Although the strength of C30-S-15 was low, its 56d strength could still reach 61.1MPa. It could be seen that the increase of stone powder content from 9% to 15% had little effect on the strength of C30 concrete. The strength of C40 concrete decreased with the increase of stone powder content. At 56d, the strength of C40-S-9 group was 70.8MPa, and that of C40-S-15 group was 65.6MPa. It could be seen that the weakening effect of stone powder content on the compressive strength of high strength concrete was more prominent. On the other hand, by comparing the strength data of concrete with different W/B at the same age, it could be seen that the change of W/B had little effect on the early strength of concrete at 9% and 12% dosage.

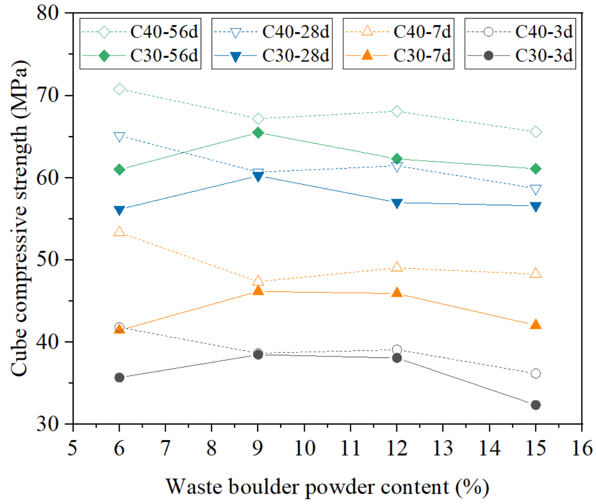

Fig. 4 Effect of waste boulder powder content on cube compressive strength of concrete

The influence mechanism of limestone powder on the mechanical properties of concrete has been widely studied, which could be divided into microcrystalline nucleation, micro aggregate and micro chemical action. Soroka et al. [19,20] found that calcium carbonate powder particles could absorb the ions of hydration products, make C-S-H grow continuously on their own particle surface, promote the migration of C3S particle surface ions in cement clinker to aqueous solution, thus accelerate the hydration of C3S, and significantly advance the nucleation time of $Ca(OH)_2$.

Secondly, the stone powder particles with the maximum particle size less than 75μm could fill the voids between the cementitious material particles, replacing the excess free water existing in the voids, optimizing the particle accumulation mode, reducing the water consumption and average pore size [21], and improving the compactness of the slurry; At the same time, its tiny particles could play a "Ball Effect", improve the fluidity of the fresh slurry, and reduce the risk of large pores due to insufficient vibration in the moulding process.

In addition, limestone manufactured sand powder has weak chemical activity. According to the research of K. D. Weerdt et al. [22], micro particles of calcium carbonate powder will dissolve carbonate ions into the slurry aqueous solution, which could react with aluminum phase in Portland cement to form hard single carbon calcium carboaluminate and semi-carbon calcium carboaluminate, which will consume Ca(OH)2, inhibiting the transformation of aft into AFm [23]. Finally, the average pore size of concrete paste is refined, and the strength of concrete is improved. These three kinds of actions make the early strength of manufactured sand concrete containing proper amount of stone powder increased rapidly. However, as a kind of inert material in the traditional sense, limestone rock powder itself could not provide outstanding cementitious and pozzolanic activity. Once the content of limestone rock powder was too high, its tiny particles will introduce too many low cohesive interface transition zone, which makes the slurry appear more thin and weak zone, resulting in the weakening of concrete hardening strength.

Therefore, for the concrete with different cementitious material dosage and strength requirements, there are differences in the optimal stone powder content of manufactured sand. As shown in Figure 4, the stone powder content of C30 concrete is about 9%, and that of C40 concrete is about 6%, which is close to the existing research [24].

3.3 Elastic modulus

The elastic modulus could reflect the constitutive relation of concrete after hardening, and it is an important mechanical property index of concrete. Table 2 showed the elastic modulus test results of waste boulder powder concrete. It could be seen that the elastic modulus of concrete will be slightly reduced when the content of manufactured sand powder increased from 9% to 15%. Increasing the content of stone powder was equivalent to replacing the dense sand particles with loose powder particles, that is, the volume of concrete slurry increased, the content of coarse particles which play the main role of skeleton decreased, and the elastic modulus decreased. On the other hand, when the W/B increased, hydrated products contained more calcium silicate hydrate gel, and the microstructure of the slurry was denser, which was conducive to enhancing the elastic modulus of the slurry. When the W/B increased, there were more pores in the microstructure, higher air content, lower compactness and smaller elastic modulus.

Elastic modulus and compressive strength were important basic parameters of concrete, which were closely related to W/B, material composition, curing age and microstructure. Considering the uncertainty of concrete test, the effective prediction probability model of concrete elastic modulus was summarized based on compressive strength. Referring to the Chinese Standard *Code for design of concrete structures (GB 50010–2010)*, formula (1) prediction model was adopted in many literatures.

$$E_c = 10^5/(2.2+34.7/f_c) \tag{1}$$

Where f_c is the compressive strength of concrete, E_c is the elastic modulus.

There were also many researchers using the power function model of formula (2), and the relevant institutions in Norway (NS) and the United States (ACI) recommend using formula (3) ~ (5) respectively:

$$E_c=(a\times f_c^{0.5}+b)\times 10^4 \tag{2}$$

NS 3493: $$E_c = 9.5 f_c^{0.3} \tag{3}$$

ACI 363: $$E_c = 3.32 f_c^{0.5}+6.9 \tag{4}$$

ACI 318: $$E_c = 4.73 f_c^{0.5} \tag{5}$$

Where f_c and E_c have the same meanings as above. In equation (2), a and b are regression constants.

According to the test results and referring to equation (2), we used the power function model of equation (6) for regression analysis:

$$E_c = 40.6+1.1\times 10^{-41} f_c^{22.7} \tag{6}$$

It could be seen from Figure 5 that the regression curve of equation (6) was more consistent with the change rule of test data. In order to further analyze the calculation accuracy of formula (6) for the test results of each mix proportion specimen, the following prediction error was defined:

$$e_{E_c} = \frac{100}{\max\limits_{i=1,2,\cdots,N}(|E_{ci}|,|E_{ci}'|)}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_{ci}-E_{ci}')^2} \tag{7}$$

Where, e_{Ec} was the prediction error of concrete elastic modulus, %; The subscript i referred to the i-th mix proportion in Table 1, and N was the total number of mix proportion, which was taken as 8; E_{ci} and E_{ci}' were the measured value and calculated value of the elastic modulus of the i-th mix proportion specimen. The final calculation result of e_{Ec} in equation (6) was 2.65%, in formula (1) ~ formula (5) was 14.04%, 9.09%, 21.71%, 21.10% and 11.79% respectively (a and b in formula (1) was 0.26 and 1.8 respectively). It could be seen that the power function model (6) proposed in this paper had higher prediction accuracy.

Table 2 Effect of manufactured sand powder content on elastic modulus of concrete (GPa)

Age/d	C30-S-9	C30-S-15	C40-S-9	C40-S-15
28	41.555	40.382	43.058	42.939
56	42.197	40.952	44.646	43.391

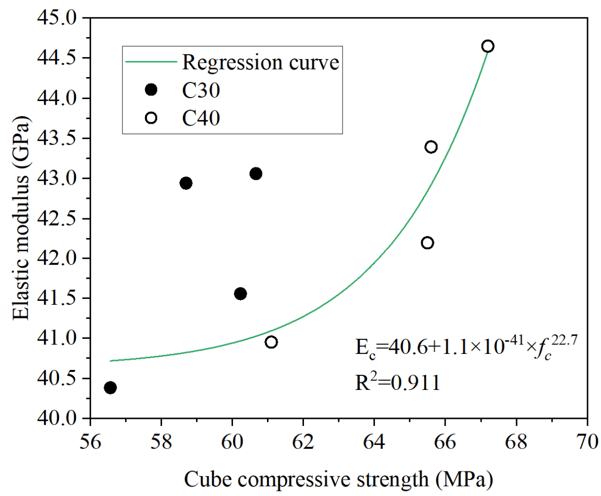

Fig. 5 Correlation between elastic modulus and cube compressive strength of concrete

4 Conclusion

In this paper, the waste boulder powder formed in the process of manufactured sand production was mixed into manufactured sand concrete by 6%, 9%, 12% and 15% respectively to prepare green environment-friendly concrete. The conclusions were as follows

(1) When the content of stone powder was more than 12%, the fluidity of fresh paste could be improved, and the fluidity will be weakened if the content of stone powder was further increased.

(2) With the increase of stone powder content, the elastic modulus of hardened paste decreased, the compressive strength of C30 concrete first increased and

then decreased, and the strength of C40 concrete continued to decrease.

(3) A mathematical model for predicting the elastic modulus of concrete by using the compressive strength of waste boulder powder was proposed, which had higher accuracy than the model in the existing specifications.

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