Research on the Performance of Manufactured Sand Concrete with Different Stone Powder Content

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Abstract. The working performance and durability of medium and low strength machine-made sand concrete with different stone powder contents were studied, and the optimal range of stone powder content in machine-made sand concrete was explored. The results show that an appropriate amount of stone powder has a significant impact on the performance of machine-made sand concrete, which can increase the volume of the slurry and increase the density of the concrete, thereby improving the crack resistance of the concrete and reducing the permeability of chloride ions. Comprehensive analysis shows that the optimal range of stone powder content (mass fraction) is between 10% and 15%. In this range, the chloride ion permeability of machine-made sand concrete decreases with the increase of the stone powder content, and the dynamic elastic modulus decreases slightly with the increase of the stone powder content, but the amplitude is small (only 2%), so it is mixed A proper amount of stone powder can improve the aggregate gradation, increase the density of concrete, and improve the advantages of poor concrete workability.

1 Preface

With the country's ban on the mining of river sand and the appeal for the development of ecological civilization, the price of natural sand has risen, and subsequently the price of concrete has risen. The exploitation of a large amount of natural sand destroys the ecological environment[1]. With the depletion of resources, natural sand, which is an essential building material, has become more and more difficult to purchase, which has seriously affected the healthy development of the construction industry. Therefore, research on mechanism sand is also in line with the needs of the times. Especially for the mountainous southwestern region of my country, natural sand is as precious as gold, so it is a general trend to study machine-made sand instead of natural sand. The appearance of natural sand and machine-made sand is very different[2]. Natural sand is light yellow while the color of machine-made sand is determined by the parent rock, but most of them are off-white and gray. Since the machine-made sand will have a certain amount of "fine powder" due to the machine in the production process, if these powder materials are not used reasonably, it will cause great harm to the surrounding environment and waste a lot of money to deal with these powders rubbish. Therefore, it is very necessary to study the machine-made sand concrete with different stone powder content. On the one hand, it can alleviate the shortage of natural sand resources on the market and ensure the price of construction materials[3]. On the other hand, it can reasonably turn waste into treasure and mix stone powder into machine-made sand concrete to improve the overall performance of concrete.

The machine-made sand contains stone powder with a particle size of less than 0.075 mm, which is one of the significant differences between machine-made sand and natural sand[4]. Stone powder is a by-product of machine-made sand. If it is not used, it will cause secondary pollution. Currently, there is no better way to deal with it. It is necessary to study high-volume stone powder concrete. At present, the research on machine-made sand concrete has been maturely applied to the construction of a bridge in foreign countries such as the United States in the 1940s. my country began to study machine-made sand in the 1980s. An example of the application of machine-made sand in my country is the construction of the Three Gorges Dam. It is a high-volume machine-made sand concrete, which is a mixture of machine-made sand, fly ash, silica fume, etc[5]. and natural sand, but no stone powder is added. In view of the small amount of cementitious material used in my country's current low and medium strength concrete, in order to meet the requirements of pumping construction and economic efficiency, the general water glue is relatively large, which will cause the problem of bleeding and segregation in low and medium strength concrete[6]. The stone powder in the machine-made sand has finer particles and a smooth surface due to the grinding of the machine, which has a "ball effect", which can not only fill the gaps of the machine-made sand, enrich the aggregate gradation, and improve the working performance of the concrete, but also has the activity. After the hydration reaction, the strength and

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compactness of concrete can be further strengthened, thereby improving the durability of concrete such as impermeability[7]. At present, there has not been a systematic study on the mechanical properties and durability (crack resistance) of stone powder mixed into low and medium strength concrete. Through the electric flux test and the flat crack resistance test, the influence of different stone powder content on the resistance to chloride ion permeability and crack resistance of concrete was tested. Through research and analysis of the influence of mixing stone powder on the working performance, mechanical properties and durability of machine-made sand concrete in different environments, the effect of different stone powder content on machine-made sand concrete shrinkage, chloride ion permeability and crack resistance is studied. The flat anti-cracking method was used to analyze the early cracking of concrete, and the electric flux method was used to explore its chloride ion permeability[8]. So as to provide technical guidance and theoretical basis for the reasonable range of the mixing amount of medium and low strength machine-made sand concrete.

2 Test overview

2.1 Experiment material

In order to carry out research on the performance of machine-made sand concrete with stone powder content, the P.O 42.5 cement from Qijianshang Concrete Station in Gansu Province was used in the experiment[9]. The physical properties of the cement are shown in Table 1, and they all meet the requirements of the specification. The fine aggregate is made of machine-made sand from Gansu Qijianshang Concrete Station, and the parent rock is limestone[10]. The continuous particle size gradation is medium sand in Zone II. According to (GB/T14684-2011) "Sand for Construction", the particle gradation, apparent density, methylene blue value, stone powder content and moisture content of machine-made sand are tested according to (GB/T14684-2011) "Sand for Construction". Related physical properties are shown in Table 2.

The coarse aggregate is 5~10mm and 10~25mm limestone crushed stone. After the 2:8 gradation, the apparent density is 2.63 g/cm3, the crushing index is 13.1%, the natural bulk density is 1.62 g/cm3, and the porosity is 40%. Consistent with the continuous grain size crushed stone specified in "Pebbles and Crushed Stones for Construction" (GB/T 14685-2011). The water-reducing agent adopts the liquid polycarboxylic acid high-efficiency (retarding type) water-reducing agent of "Sobute" Jiangsu Subote Company, with a water reduction rate of 1.5%. The test water is clean tap water.

Table 1. Physical performance indicators of cement

Specific surface aream^3/kg	Cement standard consistency /%	Initial jelling time /min	Final jelling time /min	Stability (test cake method)	Compressive s trength/MPa (3d)	Fracture stren gth/MPa (3d)
352	25	260	330	No cracks or warpage	21.3	4.8

Table 2. Physical and technical indicators of fine aggregate machine-made sand

Fineness modulus	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Methylene blue value /(g/kg)	Content of stone powder /%	Moisture content /%	Crushing index /%	Porosity /%
2.85	2670	1550	0.9	3.5	5.3	8.7	45

Table3. Material dosage of each component of 1m3 concrete

Specimen number	Water cement ratio	The amount of each material (kg/m^3)				
		Cement	sand	breakstone	Water	Stone powder
MS40-0%	0.44	396	721	1078	174	0
MS40-10%	0.44	356	721	1078	174	40
MS40-15%	0.44	337	721	1078	174	59
MS40-20%	0.44	317	721	1078	174	79
MS40-25%	0.44	297	721	1078	174	99
MS40-30%	0.44	277	721	1078	174	119

Table 4. Designed dimensions and relevant test specifications for each test

Test items	Size	Specification
Compressive strength	100mm×100mm×100mm cube specimen	"Standard for Test Methods of Mechanical Properties of Ordinary Concrete"
Fracture strength	100mm×100mm×100mm cube	

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	specimen	
dynamic modulus of elasticity	100mm×100mm×400mm prism	
Non-contact shrinkage test	100mm×100mm×515mm prism	
Plate crack resistance test	800mm×600mm×100mm flat sheet type	"Long-term performance and durability of ordinary concrete
Electric flux test	Diameter (100±1) mm, height (50±2) mm short cylinder	Performance test method standard"

Table 5. Working performance of fresh (machine-mixed) concrete under different stone powder content (40L)

Stone powder	Cement (kg)	Sand（kg)	Gravel (kg)	Water(kg)	Limestone Powder（kg)	water-reducing admixture (g)	Slumps (mm)	Expansion (mm)	Cohesion	segregation	Bleeding
0%	15.8	30	42.6	6.96	0	158	180	500	Poor	serious	Mild
10%	15.8	30	42.6	6.96	1.58	237	215	540	good	good	
15%	15.8	30	42.6	6.96	2.37	237	210	520	good	good	Mild
20%	15.8	30	42.6	6.96	3.16	237	220	540	good	good	
25%	15.8	30	42.6	6.96	3.95	237	220	570	good	good	
30%	15.8	30	42.6	6.96	4.74	316	205	500	general	Mild	Mild

2.2 Mix design

Through the design of comparative experiments, six groups (0%, 10%, 15%, 20%, 25%, 30%) of machine-made sand concrete tests with different stone powder content were established. Explore the effects of different stone powders on the working performance, mechanical properties and durability of low and medium strength C35 concrete, and then analyze the optimal mixing range of stone powder in the corresponding environment[11]. Ensure that each group of cement, machine-made sand, crushed stone, and water consumption remain unchanged, and ensure that the slump and expansion of each group of ready-mixed concrete are the same by controlling the water reducing agent, and finally unified curing under standard environmental conditions.

According to the "General Concrete Mix Design Regulations" (JGJ 55-2011), the mix ratio of sand-made concrete is calculated by the design method of saturated surface dry aggregate. Compared with other components of concrete, the influence of stone powder on the workability of concrete mixture It is closer to cement, so in terms of workability, stone powder can be regarded as a constituent of cementing material paste in concrete[12]. Determine the adaptation strength by formula (1), and then according to the "Guidelines for the Durability Design of Concrete Structures" for the maximum grout-to-bone ratio and water consumption of different strength grades, the grout-to-bone ratio of concrete is selected as 0.32; In principle, according to the porosity of the gravel and the sand ratio of 41%, the formula (2) can be obtained, and then the formula (3) the ratio of coarse and fine aggregates; according to the "Specifications for Durability Design of Concrete Structures" (GB/T50476-2008) , The maximum selection of water-binder ratio W/B is 0.44; from the slurry-to-bone ratio of 0.32, the combined formulas (4), (5) and (6) can be used to obtain the dosage of each component of ready-mixed concrete[13].

$$f_{cu,o} = f_{cu,k} + 1.645\sigma\ ,\ (f_{cu,k} = 35, \sigma = 5.0) \quad (1)$$

$$m_s : m_g = 41:59 \quad (2)$$

$$\frac{V_P}{V_A} = \frac{32}{68}\ ,\quad V_A = V_S + V_g = 0.68m^3 \quad (3)$$

$$\frac{W}{B} = 0.44\ ,\ B = C + F \quad (4)$$

$$\rho_b = \partial_c \rho_c + \partial_f \rho_f \quad (5)$$

$$V_P = V_w + V_b\ ,\ \frac{V_w}{V_b} = (\frac{W}{B}) \times \rho_b \quad (6)$$

2.3 Test results and analysis

Under the condition that the base mix ratio remains unchanged, that is, the grout-to-bone ratio and the sand ratio remain unchanged, the effect of machine-made sand with different stone powder content on the workability of concrete is studied. Through the adjustment of the water reducing agent, it is ensured that the mixed concrete finally meets the workability requirements.

Table 4 reflects the workability of fresh (machine-mixed) concrete under different stone powder content. From the analysis of Table 4, it can be seen that with the continuous increase of the stone powder content, the required water reducing dosage is also continuously increased. Stone powder acts as a lubricant to reduce the friction between sand and sand and improve the working capacity of concrete. Under the condition that the amount of water, cement and coarse aggregate remain unchanged, as the amount of stone powder increases, the bleeding rate of concrete decreases. A large amount of stone powder will affect the adhesion of cement paste and aggregate, and a large amount of powder aggregation will reduce the fluidity of the concrete mixture. Therefore, a water-reducing agent is needed to adjust the slump and expansion of the mixture. A proper amount of stone powder promotes the workability of the concrete mixture, and a large amount will be counterproductive.

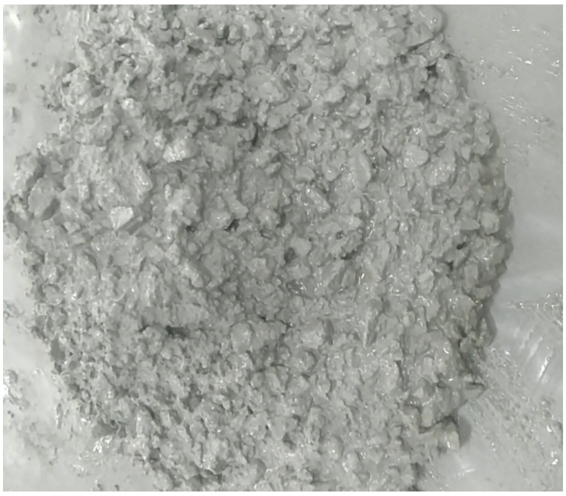
Figure (a) shows that due to the poor aggregate gradation, there are more fine particles in the coarse aggregate, the test slump and expansion are larger, segregation and bleeding, the reason is that the slurry is too small, and the aggregate leakage occurs. Adjust the coarse aggregate particle gradation, cannot form a tightly packaged state for the coarse aggregate, add 10% stone powder to obtain a concrete mixture with good workability as shown in Figure (b). The aggregates are evenly distributed, "fullness" "Glossy", with a "round feeling". Figures (c), (d) and (e) are the concrete mixed with 15%, 20% and 25% stone powder, respectively. The mixing workability is good, and the slump and expansion are both satisfied. Requirements for fluid pumping concrete.

Figure (f) shows the concrete mixed with 30% stone powder. After the adjustment of the water reducing agent, the mixing workability is moderate, the slump and expansion are slightly small, but it basically meets the requirements of large flow pumps. Requirements for sending concrete (slump and expansion of 550±50mm). Because the fine stone powder in the machine-made sand has certain activity and participates in the hydration reaction, the machine-made sand concrete needs more water than the natural sand concrete under the condition of reaching the same slump. In machine-made sand concrete, when the amount of cement and water is the same as the amount of coarse aggregate, with the increase of the stone powder content, the working performance of the concrete has been greatly improved, especially in the water retention and bleeding rate of the mixture.

(a) Mixed with 0% of limestone powder

(b) Mixed with 10% of limestone powder

(c) Mixed with 15% of limestone powder



(d) Mixed with 15% of limestone powder

(e) Mixed with 25% of Limestone Powder

(f) Mixed with 30% of Limestone Powder

Fig. 1. Working performance of machine-mixed concrete with different stone powder content

3 Mechanical performance test

3.1 Compressive strength test

Considering the physicochemical properties of stone powder and the hydration reaction products participating in it have a certain strength, stone powder is regarded as a part of the cementing material, and its mixing amount will replace part of the cement consumption. According to the broken line trend in Figure 2, the compressive strength of the test block at 7d and 28d does not change significantly with the amount of stone powder. Compared with the concrete without stone powder, the compressive strength of the test piece will be slightly increased when the stone powder is added at 10%. The reason is that a proper amount of stone powder will increase the compactness of the test piece, thereby increasing the compressive strength of the test piece. However, when the amount of stone powder reaches 30%, the cement hydration will be hindered to a certain extent due to the influence of a large amount of powder, so the strength Slightly reduced, so the recommended dosage for compressive strength stone powder is 10%~20%.

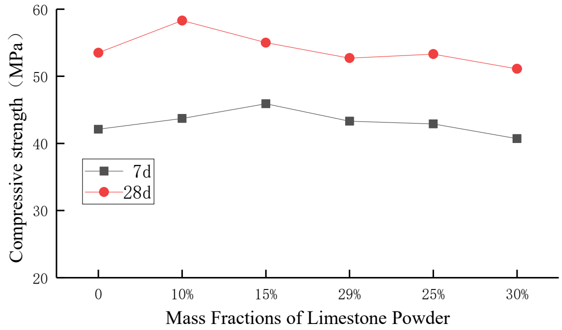


Fig. 2. The compressive strength of concrete test blocks with different stone powder content

3.2 Flexural test

Using a 100mm×100mm×400mm prism specimen for measuring the overdynamic modulus of elasticity, the integrity of the specimen is first checked, and the length and quality of the specimen are measured. Then the test piece is placed on the testing machine, and the three-point loading method is used for uniform and continuous loading. It can be seen from Figure 3 that with the increase of the stone powder content, the flexural strength of the concrete specimens generally shows a downward trend. However, the decline is not large, so there is no need to limit the mixing amount of stone powder for the flexural strength of the test piece.

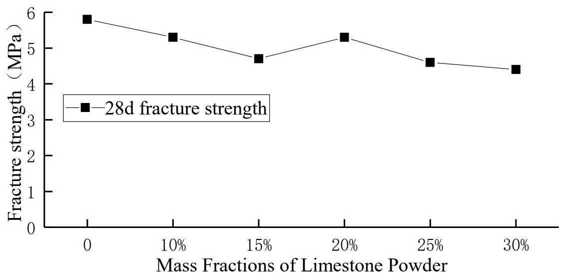


Fig. 3. The flexural strength of concrete test blocks with different stone powder content

3.3 Dynamic modulus test

It can be seen from Figure 4 that the dynamic elastic modulus value of the specimen 28d decreases as the stone powder increases. When the stone powder content is 10%, the dynamic elastic modulus value of the specimen reaches the maximum, when it exceeds 10%. The dynamic elastic modulus value of the test piece decreases with the increase of the mixing amount. Therefore, for the dynamic elastic modulus of the test piece, the recommended value of the stone powder mixing amount is 10%~15%.

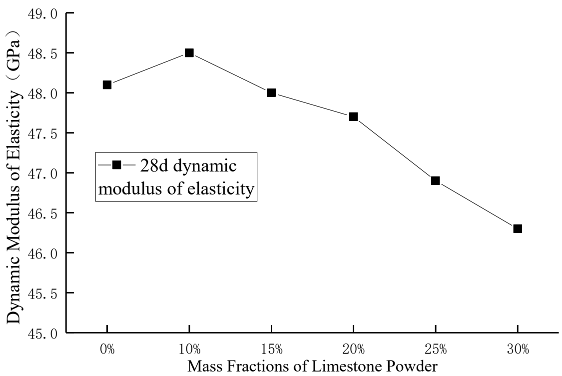


Fig. 4. Dynamic elastic modulus values of concrete specimens with different stone powder content

4 Durability test

4.1 Electric flux test

According to the NEL chloride ion diffusion coefficient method, the concrete permeability evaluation standard was used to test the chloride ion penetration resistance of concrete mixed with different stone powder content[14]. As shown in Fig5(a), the two bottom surfaces of the concrete short cylinder test block are polished and flattened, waxed, and placed in a vacuum to retain water for 20 hours. Install the test piece in the test mold, and after checking the tightness of the test block and the test mold, the prepared product is injected into the positive and negative electrode test grooves on both sides of the test piece. Set six hours to read the data and record it as a table. The test is carried out in an environment of 20°C and a humidity of 75%.

(a) The test piece is waxed and vacuum saturated

(b) Power-on test

Fig. 5. Electric flux test under different stone powder content

According to the analysis in Figure 1, the chloride ion impermeability of machine-made sand concrete with 10%~15% stone powder content is better, and the 15% content is the best. With the increase of stone powder content, it may be due to a large number of powder particles. The stone powder is wrapped on the surface of the concrete, which affects the combination of aggregate and cement paste, thereby affecting the compactness of the specimen and reducing the impermeability.

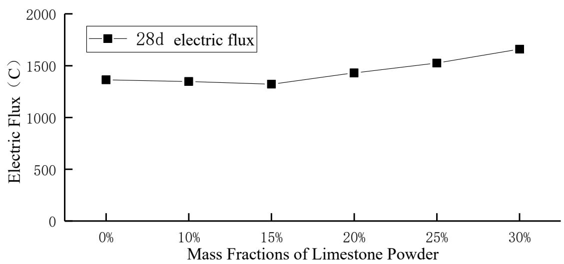
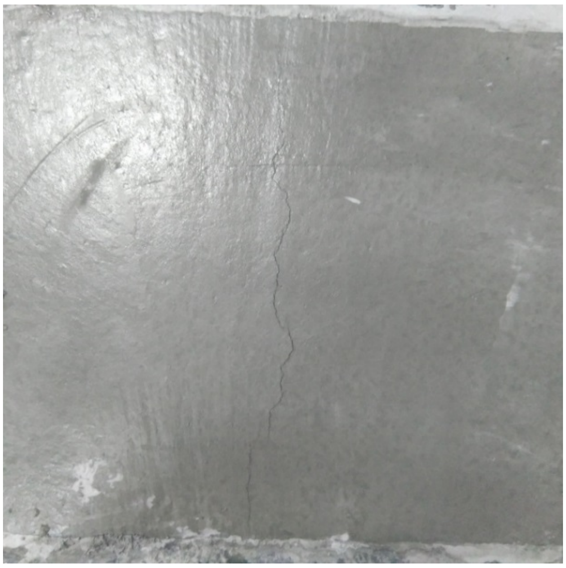


Fig. 6. The electric flux value of concrete specimens with different stone powder content

4.2 Early crack resistance test

Most of the damage of concrete specimens starts from the appearance of cracks on the surface, and then further develops and spreads. The occurrence of cracks will cause the stress redistribution of the concrete stressed members, which will affect the durability and safety of the concrete structure[15]. Therefore, ensure the durability of the concrete members. Integrity should first be studied to prevent the occurrence of cracks. Use a plane thin-plate specimen with a size of 800mm×600mm×100mm to test the early concrete crack resistance test, record the time when the first through crack appears and mark it, and then use the instrument to measure the number of cracks after the concrete is naturally cured and hardened for 24 hours Width, recorded as a table. The following figure shows the first penetrating crack on the surface of machine-made sand concrete and the mark of the number and width of cracks after 24 hours.



(a) The first through cracks appeared on the surface of the concrete

(b) The number of cracks on the concrete surface after 24h

Fig. 7. Early concrete slab crack resistance test with stone powder content

From Figure 8, the influence of stone powder content on the crack resistance of the test piece: when the content is less than 15%, the crack resistance of the test piece increases with the increase of the stone powder content, and there are fewer cracks per unit time, and the stone powder. When the content is 15%, the number of cracks is the least. Therefore, for projects with strict crack control requirements, it is recommended that the stone powder content should not exceed 15%.

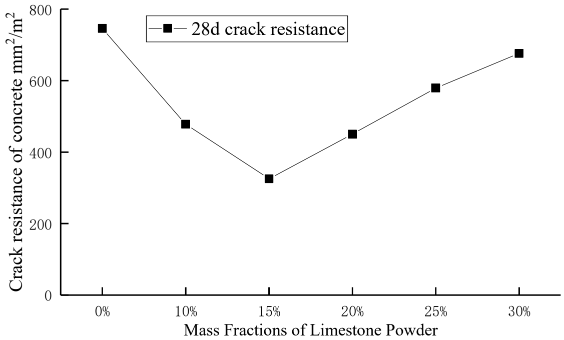


Fig. 8. 28d anti-cracking value of concrete specimens with different stone powder content

4.3 Non-contact shrinkage test

The influence of stone powder content on the 3d shrinkage rate of the test block: according to Figure 9. The shrinkage rate of the concrete test block increases with the increase of the stone powder content. When the content of stone powder is 10%, the water requirement of stone powder at this content is not obvious, and the required water reducer is also less different than that of no stone powder, and the drying shrinkage rate of the test piece is the smallest. Therefore, stone powder is recommended for the drying shrinkage rate. The dosage is 10%.

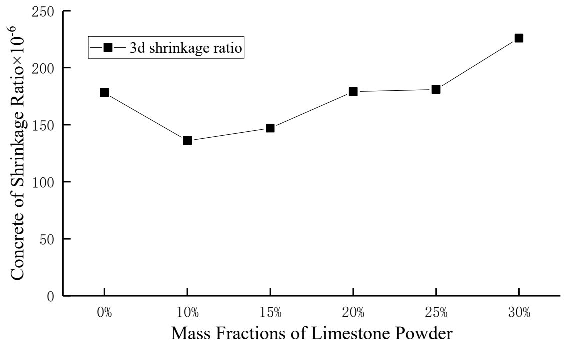


Fig. 9. 3d shrinkage rate of concrete specimens with different stone powder content

Under different environmental conditions, the optimum range of stone powder content for medium and low strength machine made sand concrete is 10%-20% for compressive strength; it has almost no effect on the flexural stone powder content; it has little effect on the dynamic elastic modulus of concrete. The optimal range of stone powder mixing amount is 10%-15%; the filling effect and crystal nucleation effect of stone powder make the concrete denser, so for the requirements of early anti-cracking performance of concrete, the recommended value of reasonable stone powder mixing amount is 10%-20 %; For the chloride ion penetration test, when the stone powder content is 15%, the concrete has the strongest resistance to chloride ion penetration, and when the stone powder content exceeds 20%, the chloride ion penetration performance will become very large. It is not conducive to the durability of concrete. Through comprehensive experimental research and analysis, in the mechanism of concrete, the recommended mixing amount of stone powder is 10% to 15%, and the maximum mixing amount is not more than 15%.

5 Conclusion

As a new material that can replace natural sand, machine-made sand concrete will surely make the concrete industry more stable. To study the correlation between the mechanical properties, working properties and durability of medium and low strength concrete and the dosage of stone powder. The research results have important theoretical and practical significance on the influence of the amount of stone powder and the performance of concrete. Study the optimal mixing amount of stone powder in concrete, and revise our country to learn from other countries on the mixing amount of stone powder in concrete. Stone powder plays an irreplaceable role in machine-made sand concrete. As a kind of fine powder particles, the stone powder in machine-made sand makes the particles finer and has a smooth surface due to the grinding of the machine. It has a "ball effect" and can not only fill the machine. Sand voids and rich aggregate gradation filling efficiency is high, improving the work performance of concrete, and its activity, after hydration reaction, can further strengthen the strength and compactness of concrete, thereby improving the durability of concrete such as impermeability . Because the machine-made sand comes from the mechanical crushing of the mountain rock, the composition is relatively homogeneous, and there is no debris, and the particle surface is rough and polygonal due to mechanical crushing, etc., so it has a good combination with cement and gravel, and has a good mechanical bite force. High, so the strength of the prepared concrete is slightly higher. Based on the research results, the following conclusions can be drawn:

• For machine-made sand concrete, a mix ratio design method that is different from the traditional design method is adopted, and the saturated surface dry method is used to calculate the amount of each component material. As a kind of semi-inert and semi-reactive material, stone powder has a good positive influence in the mixture. Therefore, under the premise of satisfying the various properties of concrete, it is reasonable to calculate the influence of the mixing amount of stone powder on the late durability performance of machine-made sand. It has a positive meaning. The stone powder particles are relatively fine, which can partially fill some gaps, which reduces the use of cementitious materials to a certain extent and greatly improves the economy.

• As a fine particle composition, stone powder can not only improve the working performance of machine-made sand concrete (reduce the occurrence of segregation and bleeding), but also because of the particle effect of stone powder, it makes the aggregate gradation more abundant, the concrete is more dense, and the concrete is greatly improved. The impermeability of chloride ions. It also reduces the appearance of early cracks in the concrete specimens, and the compressive strength (bearing capacity) of the specimens is slightly improved.

• The experiment adjusts the workability of the machine-made sand concrete at each dosage by using water-reducing agent. As the experiment progresses, it is concluded that when the amount of stone powder is greater than 15%, the demand for water-reducing agent begins to increase, which proves that a large amount of stone powder has a greater demand for water, and the mixing method of water-reducing agent is recommended Adopt post-doping method. The experimental study found that in the six test gradients, stone powder content of 10%-15% has good enthusiasm for concrete compressive strength, flexural tensile strength and dynamic elastic modulus. Concrete with high content of stone powder is more sensitive to cracking.

• Stone powder is also involved in the hydration of part of the cement. Therefore, it can be considered to replace part of fly ash with stone powder when a large amount of mineral admixtures are added. That is, mixing stone powder and fly ash can greatly improve the performance of machine-made sand concrete. Workability, on the other hand, can also improve the durability of concrete. Moreover, the incorporation of stone powder greatly improves the early crack resistance of concrete, can reduce the early cracking sensitivity of machine-made sand concrete, and greatly improve the service life and integrity of concrete specimens and structures.

References

1. HASDEMIR S, TUĞRUL A, YLMAZ M. The effect of natural sand composition on concrete strength. CBM, (2016)
2. Goncalves J P, Tavares L M, Toledo F R D, et al. Comparision of natural and manufactured fine aggregates in cement mortars[J]. CCR, **27**, 3 (2017)
3. Xie Kaizhong, Liu Zhenwei, Zhu Maojin, Ma Dali. Mechanical properties of machine-made sand concrete with different stone powder content after high temperature[J]. JOBE, **38** (2021)
4. Wang Jiliang. Research on the influence of the properties of machine-made sand on the performance of concrete and its mechanism [D]. WUT, **23** (2081)
5. Yu Honda, Chen Yanfei, Wang Huan, Li Xiudong, Xie Chao, Li Sheng. Experiment on the suppression of shrinkage and cracking of high-strength machine-made sand concrete with high content of high adsorptive stone powder[J/OL].J COMPOS MATER,**56** (2021)
6. Tong Xiaogen, Zhang Kaifeng, Meng Gang, Luo Zuoqiu, Hu Yubo, Wang Jiamin, Wang Bo, Wang Guofeng. The effect of machine-made sand-stone chips composite fine aggregate on the performance of concrete with different strength grades[J]. Bulletin of the Chinese Ceramic Society, **72**,3(2021)

7. Xia Jingliang, Gao Yanpeng, Zhang Pengxiang, Guan Qingfeng, Wang Jing, Zhou Yongxiang. Influence of MB value of machine-made sand on concrete electric flux and chloride ion diffusion coefficient[J]. BS,**37**,3 (2021)
8. Xu Zhihua, Deng Junshuang, Liu Zhanao, Li Beixing, Zhou Mingkai. Research on the influence of MB value of fine powder in machine-made sand on concrete performance[J/OL]. WUT, **13**, 6 (2021)
9. CEPURITIS R, JACOBSEN S, ONNELA T. Sand production with VSI crushing and air classification: Optimising fines grading for concrete production with micro-proportioning. MINER ENG, **78**(2016)
10. Wang Xuhao, Gan Long, Yu Haiyang, Li Cheng, Gao Xinmin, Zhang Yagang, Li Lianwei, Bian Qinghua. Influence of stone powder content on performance of C45 tuff machine-made sand concrete[J]. Bulletin of the Chinese Ceramic Society, **19**,4(2021)
11. Metha P K. Principles underlying production of high-performance concrete. CCA,**12**,2 (1990)
12. Jiang Zhengwu, Ren Qixin, Wu Jianlin, Zhang Changgui. Research on the characteristics of machine-made sand and its application in concrete [A]. China Sand and Stone Association. Paper Collection of the First Forum on Machine-made Sand Production and Application Technology [C]. China Sand and Stone Association: China Sand and Stone Association, (2010)
13. Zhou M K, Peng S M, Xu J. Effect of stone powder on stone chippings concrete. J WUHAN UNIV TECHNOL, **4**, 11(1996)
14. Li Zhou. Research on the influence of stone powder on the properties of machine-made sand and its mortar and concrete[D]. CSUST, (2019)
15. Zhang Dapeng, Yang Jianglin, Shao Yu. Experimental study on the working performance and durability of limestone machine-made sand concrete[J]. Concrete World, **73** (2021)