Study on Application of Machine-made Sand Self compacting Concrete in Tunnel Secondary Lining

Xiaomiao Huang[1,a], Qi Gao [1,b], Guihong Dong * [2,3,c]

[1]The Sixth Engineering Company of CCCC Fourth Harbor Engineering Co.,Ltd, Zhuhai 519085, China
[2]GuangZhou Harbor Engineering Quality Examination Co,.Ltd ,Guangzhou 510230,China
[3]CCCC Fourth Harbor Engineering Institute Co., Ltd, Guangzhou 510230,China

[a]hxiaomiao@cccc4.com, [b]gqi@cccc4.com, [c]dguihong@cccc4.com

Abstract. An environmentally friendly self-compacting concrete for tunnel lining was prepared by replacing river sand with mechanism sand, adding appropriate amounts of stone powder and fly ash to adjust the workability and reduce cement consumption. After studying the effects of different coarse aggregate gradations, sand ratios, stone powder contents, and fly ash contents on the workability of the self-compacting concrete, the optimal mix proportion was determined. The best results were obtained when the coarse fine aggregate proportion was 6:4, the sand ratio was 0.43, the stone powder content was 5%, the fly ash content was 25%, and the water-cement ratio was 0.32, which met the engineering strength requirements. This provides a theoretical basis for the application of mechanism sand self-compacting concrete in tunnel secondary lining works.

Keywords: Mechanism sand, self-compacting concrete, workability, stone powder, tunnel secondary lining

1 Introduction

With the increase in scale and grade of construction projects in China, the complexity of structural reinforcement and the difficulty of construction have risen, while skilled workers are becoming increasingly scarce. Consequently, the quality of engineering projects often cannot be guaranteed due to improper concrete compaction, leading to challenges in ensuring the quality, efficiency, and benefits of construction projects[1~3]. Additionally, the issue of noise pollution from concrete compaction in urban areas urgently needs to be addressed[4~6]. Secondary lining concrete is a vital component of tunnel structures, serving as the final line of defense for waterproofing and directly reflecting the aesthetic appearance of tunnels. Typically, secondary lining concrete in tunnels adopts C20~C35 waterproof concrete, which does not have high strength requirements. However, due to the narrow construction areas and difficulty in compaction, it demands high workability of the concrete. Therefore, conventional self-compacting concrete requires a large amount of cementitious materials to ensure its work-

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ability[7]. As a high-performance concrete that does not require vibration for compaction but can fill all corners of the formwork with good flowability and permeability, self-compacting concrete has significant advantages in secondary lining construction.

In recent years, especially in the southwestern region, the scarcity of river sand resources has led to the utilization of manufactured sand in the preparation of self-compacting concrete, which has started to enter the engineering application stage. Compared to natural river sand, manufactured sand particles are sharp and angular, with a higher fineness modulus and poor gradation, resulting in a higher void ratio when stacked. Consequently, the preparation of self-compacting concrete with manufactured sand requires a larger water dosage, making it prone to segregation and bleeding, and often resulting in inferior appearance quality. Therefore, developing self-compacting concrete with low cementitious material dosage using manufactured sand is crucial for the technical and economic feasibility of concrete structures. The tunnel industry in Japan is facing a shortage of labor, leading to the development of an automated method using self-compacting concrete (SCC) for tunnel secondary lining construction. SCC is a material that can be constructed without vibration, and taking advantage of this characteristic, attempts have been made to use concrete pump trucks for SCC in secondary lining construction. Full-sized experiments have shown that the construction of SCC can be completed without skilled workers, which helps reduce labor while improving construction quality and safety[8~10].

This study investigates the preparation method of self-compacting concrete for secondary lining in tunnels using manufactured sand. The influences of coarse aggregate gradation, sand ratio, and limestone powder on the workability of self-compacting concrete are explored, and the optimal mix proportion for self-compacting concrete with manufactured sand is proposed[11~14].

2 Experiment

2.1 Raw Materials

(1)Cement: PO 42.5 cement produced by a cement company in Hunan, with its main physical properties listed in Table 1.

(2)Fly Ash: Grade II fly ash from a power plant in Guangxi, with its main physical properties listed in Table 2.

(3)Limestone Powder: Recycled powder from the production process of manufactured sand, with its main properties listed in Table 3.

Table 1. Physical Properties of Cement

Specific Surface Area	Density /(g . cm^{-3})	Standard Consistency/%	Setting Time /min		Compressive Strength /MPa		Flexural Strength/MPa	
			Initial	Final	3d	28d	3d	28d
348.0	3.15	27.6	183	250	30.2	53.1	5.6	11.2

Table 2. Physical Properties of Fly Ash

Testing Items	Grade II Fly Ash Standards	Test Results
Fineness	≤25.0	10
Moisture Content /%	≤1.0	0.1
Water Requirement Ratio/%	≤105	101
Loss on Ignition/%	≤8.0	3.58
Density /(g . cm^{-3})	−	2.2

Table 3. Physical Properties of Limestone Powder

Testing Items	Standards	Test Results
Fineness	≤15.0	10
Moisture Content /%	≤1.0	0.3
Density /(g . cm^{-3})	−	2.8

(4)Fine Aggregate: The manufactured sand has a flat and elongated crushed stone content of 5.0%, with a continuous particle size distribution. The limestone powder content is 8%. The apparent density is 2700 kg/m3, with a fineness modulus of 3.01, classified as Zone II sand. The particle size distribution curve is shown in Fig. 1.

(5)Coarse Aggregate: Two grades of crushed stone, with maximum nominal particle sizes of 5-10mm and 10-20mm respectively, are selected as fine and coarse aggregates. The apparent density of the crushed stone is 2720 kg/m3, with a crushing value of 10% and a water absorption rate of 0.21%.

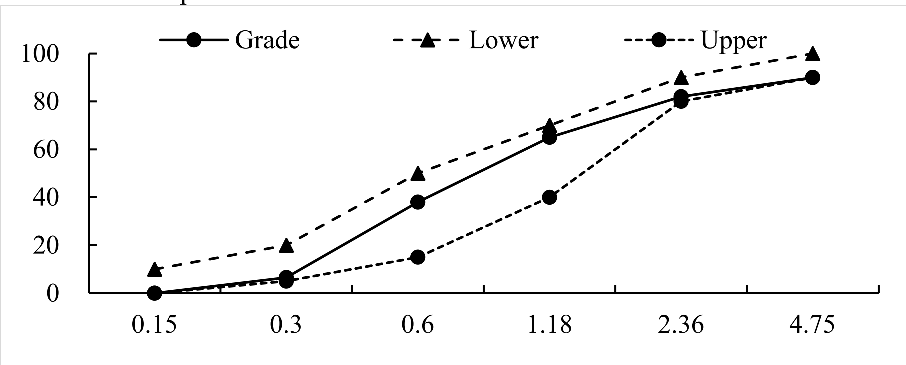

Fig. 1. Gradation Curve of Manufactured Sand

(6)Admixture: JM-PCA(I) polycarboxylate superplasticizer (retarding type) produced by Jiangsu Subote New Materials Co., Ltd.

2.2 Test Methods

(1)Test the slump, T500, and J-ring expansion of self-compacting concrete according to the relevant standards of "Technical Specification for Application of Self-Compacting Concrete" (JGJ/T 283-2012), as shown in Table 4 for the mix proportions, the related experiments are shown in Fig. 2.

(2)Use the sieve segregation method to measure the segregation resistance of self-compacting concrete, with the sieve passing amount reflecting the segregation resistance. The specific operation is as follows: fill a segregation resistance barrel with 10L of freshly mixed concrete, let it stand for 15 minutes, then pass the upper part of the concrete through a standard sieve with a square hole size of 4.75mm, weigh it after 2 minutes, remove the sieve and the concrete in it, and weigh the weight of the mortar flowing through the sieve. The ratio of the two is the sieve passing rate.

(3)Use a rheometer to test the rheological properties of cement paste. Fill the prepared cement mortar into a glass beaker, then fix it on the rheometer platform, collect data under the predetermined program to draw the rheological curve, and use the least squares method to fit the rheological curve, from which the yield stress τ and plastic viscosity value η of the mortar can be calculated.

Fig. 2. The related experiments

Table 4. Mechanical sand self-compacting concrete mix design

ID	Ratio of 5-10mm to 10-20mm stone size	Cementitious Material Usage/kg/m³	Fine Aggregate Usage/kg/m³	Coarse Aggregate Usage/kg/m³	Additive Usage/kg/m³	Water Usage/kg/m³
1	2:8	520	756	887	5.20	171
2	3:7	550	756	887	5.50	181
3	3:7	520	789	854	5.20	182
4	4:6	520	822	822	5.20	182
5	5:5	520	854	789	4.68	175
6	5:5	520	854	789	4.68	175
7	5:5	520	821.5	821.5	5.20	182
8	5:5	520	887	756	4.68	174
9	6:4	520	854	789	4.68	175
10	6:4	520	887	756	4.68	175
11	5:5	520	854	789	4.68	177
12	6:4	520	854	789	4.68	176
13	6:4	520	854	789	4.98	180
14	5:5	520	854	789	5.20	176
15	5:5	520	854	789	5.72	180
16	6:4	520	854	789	5.20	180
17	5:5	520	854	789	5.20	180

3 Results and Discussion

3.1 Influence of Coarse Aggregate Gradation on the Workability of Self-Compacting Concrete

The research investigates the workability of self-compacting concrete under the conditions of water-binder ratio of 0.32, sand-to-cement ratio of 0.45, stone powder content of 0, and fly ash content of 30%, with the fine-to-coarse stone ratios of 2:8, 3:7, 6:4, and 5:5. The experimental results are shown in Fig. 3.

Fig. 3 shows that when the fine-to-coarse aggregate ratio is 6:4, the self-compacting concrete exhibits the least degree of segregation percentage, demonstrating the best resistance to segregation. Furthermore, from Figure 2, it can be observed that when the fine-to-coarse aggregate ratio is 6:4, the slump expansion and J-ring expansion reach their maximum values, with the smallest difference between them, indicating good workability and passability. In contrast, when the fine-to-coarse aggregate ratio is 8:2, the concrete exhibits severe segregation, and the difference between the slump expansion and J-ring expansion is larger. Therefore, it can be concluded that the aggregate gradation has a significant impact on the resistance to segregation of self-compacting concrete. The better the resistance to segregation, the better the workability and passability of the self-compacting concrete.

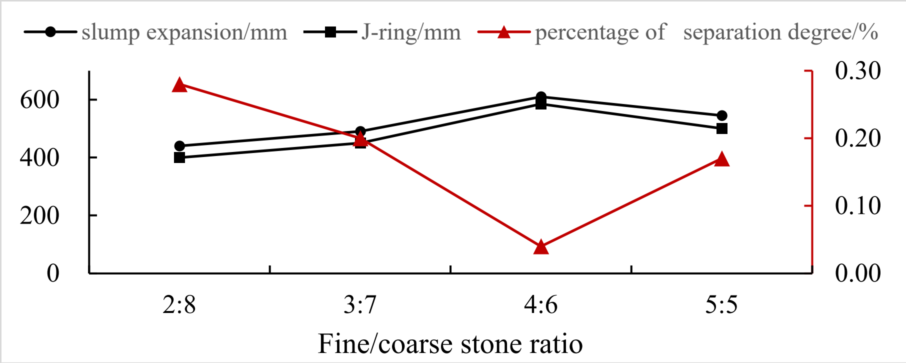

Fig. 3. The Influence of Coarse Aggregate Gradation on Workability

3.2 The Influence of Stone Powder Content on the Workability of Self-Compacting Concrete

Stone powder is recycled powder from the processing of machine-made sand, which has characteristics such as round particle shape and smooth surface. Considering stone powder as a kind of cementitious material, replacing a small amount of cement, it is incorporated into self-compacting concrete to increase the composition of fine powder and improve the working performance of self-compacting concrete, while effectively reducing its self-shrinkage deformation. Under the conditions of a coarse-to-fine aggregate ratio of 6:4, a water-to-binder ratio of 0.32, a sand ratio of 0.43, and a 30% fly ash content, the impact of the replacement of cement with stone powder on the working performance of self-compacting concrete was investigated, as shown in Figure 4. The results show that self-compacting concrete was successfully formulated without the use of chemical rheological modification agents under the circumstance of adding stone powder.

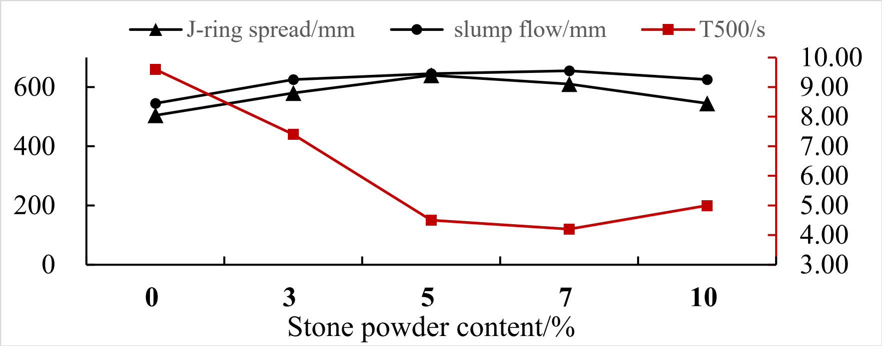

Fig. 4. Effect of stone powder content on working performance

From Fig. 4, it can be clearly seen that the addition of stone powder significantly enhances the fluidity of concrete. With the increase of stone powder content, the slump flow of concrete shows a gradually increasing trend. When the content reaches 7%, the slump flow of concrete reaches the highest value of 655mm, and then slightly decreases. Correspondingly, the J-ring flow also first shows an upward trend and then gradually decreases. When the stone powder content is 5%, the J-ring flow reaches the highest value of 640mm. At this time, the difference between the slump flow and J-ring flow of self-compacting concrete is only 10mm, indicating that the permeability of the concrete system has also reached the optimal state. As a fine aggregate, stone powder fills the particle size difference between cementitious materials and fine aggregates, optimizing the rheological properties of the concrete system. The yield value of self-compacting concrete using stone powder as an additive is lower, and it maintains a relatively high fluidity of concrete without appearing layering. However, since stone powder is a relatively inert material, excessive replacement of cement will reduce the adhesion force between the paste and the aggregates, resulting in poor permeability of concrete and rapid decrease in J-ring flow.

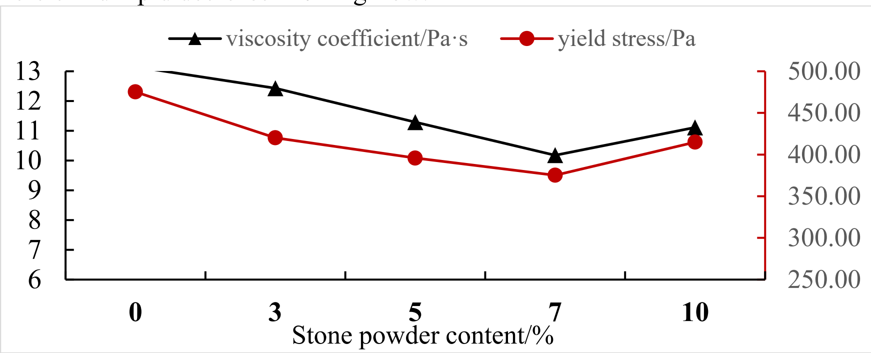

Fig. 5. Impact of stone powder content on rheological properties

From Fig. 5, we used a rheometer to study the rheological properties of cement mortar with varying stone powder content. Least squares method was used to obtain the viscosity coefficient and yield stress of each mortar group. Results showed that adding stone powder effectively reduced yield stress and improved rheological properties at an appropriate dosage. However, beyond 5% content, paste viscosity remained stagnant, and yield stress started increasing once content exceeded 7%. Optimal results were achieved at 5% content as it filled the gaps between fine aggregates and cementitious materials. Comprehensive concrete working performance was seen to reach its optimal state.

Stone powder has a minor impact on concrete compressive strength at low dosage. However, when the content exceeds 5%, the strength decreases since the inactive stone powder cannot fill the pores generated. Therefore, an optimal content of 5% is recommended to balance filling and strength. This ensures concrete has good rheological properties without decreasing strength.

4 Conclusion

The main research focused on the effects of coarse aggregate gradation, sand ratio, and stone powder content on the working performance of self-compacting concrete. The results showed that:

(1) The coarse aggregate gradation has a significant impact on the anti-segregation performance and workability of self-compacting concrete. It was found that under the condition of a coarse-to-fine aggregate ratio of 6:4, the concrete has the best anti-segregation performance and flowability. Therefore, attention should be paid to the matching of coarse aggregate gradation when formulating self-compacting concrete to ensure its excellent working performance.

(2) The addition of stone powder also plays a rheological modification role in self-compacting concrete. When the stone powder content is 5%, the concrete has the best workability.

(3) The optimal mix proportion of machine-made sand self-compacting double-layer lining concrete designed with workability as the evaluation index is a coarse-to-fine aggregate ratio of 6:4, a sand ratio of 48%, a stone powder content of 5%, a fly ash content of 25%, a water-to-binder ratio of 0.32, which meets the technical requirements of tunnel double-layer lining strength.

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