Experiment Study on the Paste Rheological Threshold of Magnetite Aggregate Self-compacting Concrete

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Abstract. Radiation shielding boxes in nuclear power plants suffer from dense and complex reinforcement and concrete that is not easy to vibrate. This places high demands on the flowability of concrete. In this study, the paste threshold method was used to carry out the paste threshold test on the flowability of self-compacting concrete containing magnetite and common aggregate. The test results show that: The flow of concrete containing magnetite aggregates in the same proportion is about 10% lower than that of concrete mixed with ordinary aggregates, and the T_{500} expansion time rises by 35%; and a model for calculating the paste threshold of magnetite self-compacting concrete was developed. The model provides guidance for the design of magnetite self-compacting concrete.

Keywords: Magnetite aggregates; Paste threshold method; Self-compacting concrete;

1 Introduction

Nuclear safety is related to the safety of people's lives and property, and radiation shielding is a crucial part of nuclear safety protection. Magnetite is widely used in radiation shielding, which has a high density and good shielding performance as aggregate [1]. The complex internal structure of nuclear power plants and the dense reinforcement bring great difficulties to the pouring and vibration of concrete. As a new type of concrete material, self-compacting concrete has the characteristics of high fluidity, does not need vibration, and can be used quickly [2], and can be uniformly distributed in the complex pipe network and between the gaps of steel reinforcement without segregation in engineering applications. Magnetite has a large specific gravity, which will affect the flow of concrete and even lead to segregation. In order to avoid this problem, the mix ratio design is particularly important.

There have been many researches on the proportion design methods for self-compacting concrete. Okamura [3] pioneered the concept of self-compacting concrete and proposed the empirical design method of step-by-step fitness to achieve the proportion design of self-compacting concrete from paste to mortar, and then to concrete. Nan Su [4] et al. proposed paste filler model, which was parameterised by the pile compacting

A. M. Zende et al. (eds.), *Proceedings of the 2024 3rd International Conference on Structural Seismic Resistance, Monitoring and Detection (SSRMD 2024)*, Atlantis Highlights in Engineering 27,
https://doi.org/10.2991/978-94-6463-404-4_34

factor (PF) of aggregates as the proportion design parameters, sequentially determining the admixture of aggregate, water, cement, etc., and finally adjusting the superplasticizer dosage to complete the design of the mix ratio. Ozbay [5] et al. used a statistical approach to design the mix ratio of self-compacting concrete by using the L18 orthogonal design method with six factors, namely, water/cement ratio, water content, sand ratio, fly ash content, air-entraining agent, and superplasticizer dosage, and designed a compliant proportion. Wallevik [6] proposed the vectorised rheological design method, by using the two parameters of yield strength and bond strength derived from the rheometer, according to the needs of different engineering conditions for the performance of concrete, the components were adjusted accordingly to obtain a self-compacting concrete that meets the requirements of the project. Linghui Liu [7] et al. proposed the concept of generalised self-compacting region based on the theoretical model of multilayer redundant layer by quantifying the properties of sand film thickness, paste film thickness, and aggregate stacking density and specific surface area, and responded to the robustness of self-compacting concrete through the area of generalised self-compacting region. Wu Qiong et al. established a mechanical model of self-compacting concrete based on the residual mortar film theory, and the workability of concrete was well predicted based on the threshold theory of paste. Jingbin Zhang further improved this method by considering the effects of coarse and fine aggregates respectively, and proposed a new threshold calculation formula for paste[8-11].

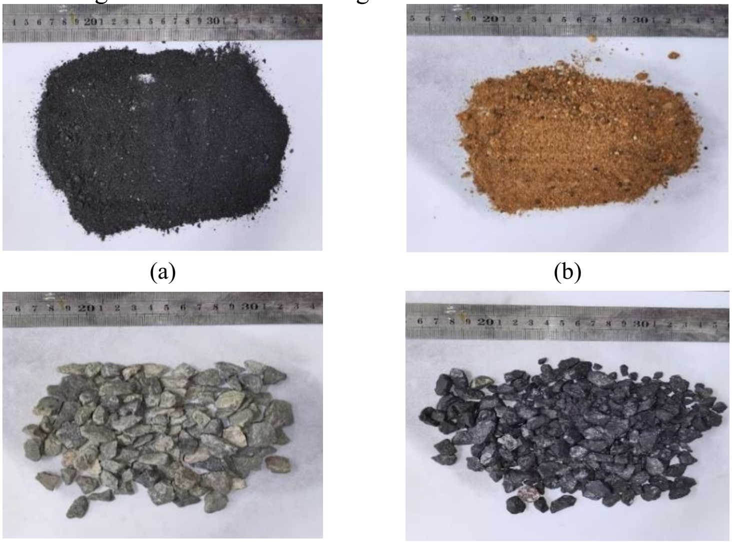
There are fewer studies on the design methods of self-compacting concrete containing magnetite. K.Sakr [12] used ilmenite and barite for the preparation of heavy concrete and the workability of the heavy concrete was decreased by 66.7%-100%.El-Sayed [13]used magnetite for the preparation of concrete and the flow of magnetite concrete was decreased by 22%, which can be improved by the use of superplasticizer. Yajun Lv [14] et al. prepared heavy concrete using hematite sand with partial replacement of sand with replacement rates of 0%, 10%, 20%, 30%, 40% and the results showed that there was a significant decrease in the flow properties with the increasing proportion of admixture. D.H.DU [15] used baryte sand with replacement of sand with replacement rates of 0%, 10%, 20%, 30% and 100%. The results show that when the displacement rate is 0, the fluidity is maximum, and when the displacement rate is 100%, the fluidity is minimum but still maintains reliable flow performance.

The paste threshold method is used to design magnetite self-compacting concrete, and the threshold model of magnetite paste is proposed.

2 Materials and Methods

2.1 Materials

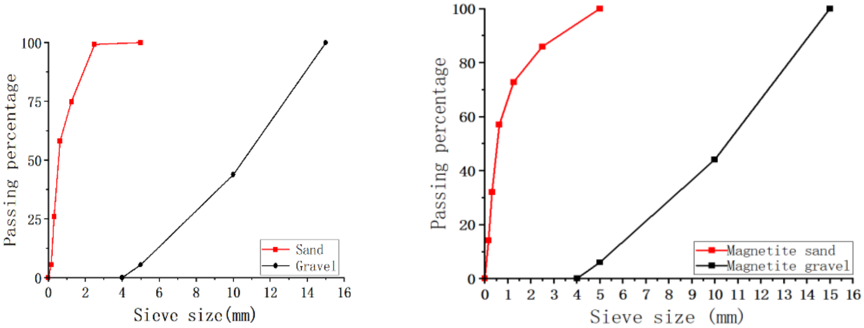
The cement is ordinary silicate P.O42.5 cement. The superplasticizer used is Subert PCA-I type. Coarse aggregate select gravel and magnetite, gravel apparent density of 2865kg/m3, bulk density of 1456kg/m3; magnetite stone apparent density of 4549kg/m3, bulk density of 2398 kg/m3. The fine aggregate selects river sand and magnetite sand, the apparent density of river sand is 2586 kg/m3, fineness modulus 2.4, belongs to II area medium sand; magnetite sand, the apparent density is 3823 kg/m3, fineness modulus 2.38, belongs to II area medium sand, the material diagram is shown in Fig.1. Screening curves are shown in Fig.2.



(a) (b)

(c) (d)

Fig. 1. Aggregate:(a)magnetite sand(b)river sand(c)gravel(d)magnetite



(a) (b)

Fig. 2. Particle size distribution curves of sand and gravel

2.2 Mix Proportion

The design of mixing proportion for powders is usually based on the volumetric water-cement ratio corresponding to the basic water requirement of the powder. The experimental method of the basic water demand rate of powder is adopted from the test method of Prof. Okamura [3], and the basic water demand rate of cement is 1.12. Therefore, the basic volumetric water-cement ratio is determined to be 1, and the step size is taken to be 0.1 for designing volumetric water-cement ratio change. Superplasticizer according to the manufacturer's recommended dosing of 0.5%, 0.6%, 0.7%. Finally, a total of nine groups of paste ratios were obtained, see Table 1.

Table 1. Mix proportion of paste

V_w/V_p	cement(g)	water(g)	sp(g)	sp%
1	937.03	302.27	3.12	0.5
1	935.66	301.83	3.74	0.6
1	934.30	301.39	4.36	0.7
1.1	892.72	316.77	2.98	0.5
1.1	891.48	316.33	3.57	0.6
1.1	890.24	315.89	4.15	0.7
1.2	852.42	329.97	2.84	0.5
1.2	851.28	329.53	3.41	0.6
1.2	850.15	329.09	3.97	0.7

According to the specifications [16-17], a basic volume water-cement ratio of 1.05, a step size of 0.05 and volumetric admixture of coarse aggregate of 0.3m^3 were selected to design nine sets of concrete tests containing gravel and river sand, and the mix ratios are shown in Table 2. Magnetite concrete were designed by the same proportions.

Table 2. Mix proportion of concrete containing gravel and river sand

V_w/V_p	cement(kg)	water(kg)	Sand(kg)	CA(kg)	sp(kg)
1.05	591.27	200.27	760.28	859.65	2.96
1.05	591.27	200.27	760.28	859.65	3.55
1.05	591.27	200.27	760.28	859.65	4.14
1.1	577.19	204.81	760.28	859.65	2.89
1.1	577.19	204.81	760.28	859.65	3.46
1.1	577.19	204.81	760.28	859.65	4.04
1.15	563.77	209.14	760.28	859.65	2.82
1.15	563.77	209.14	760.28	859.65	3.38
1.15	563.77	209.14	760.28	859.65	3.95

3 Results & Discussion

3.1 Flow Test of Self-compacting Concrete with Ordinary Aggregate and Magnetite Stone

The fluidity and T_{500} flow time of two groups of self-compacting concrete tests were tested and the results are shown in Table 3. The test pictures are shown by Fig.3.

As can be seen from Table 3 and Fig. 3, using the same volumetric admixture and the same grading, the extension of concrete containing magnetite is significantly reduced, about 10% compared to ordinary concrete, and the T500 extension time becomes longer, about 35% higher. It indicates that a significant reduction in flow properties occurs when magnetite is used as an aggregate. The reason for this phenomenon may be that the specific gravity of magnetite reaches 4.5, the density is larger, the gap between the particles is relatively small, the interlocking phenomenon occurs between the aggregates, and the friction between the aggregates is greater, leading to a reduction in the fluidity of concrete. In contrast, the specific gravity of ordinary aggregate is lower, the gap between the particles is relatively large, the interlocking effect is weaker, and the concrete flow is higher.

Table 3. Comparative experiment of concrete containing original aggregate and magnetite

Number	Magnetite concrete		Notes	Original concrete		Notes
	SF(mm)	T_{500}(s)		SF(mm)	T_{500}(s)	
1.05_0.5	220	/		499.5	21.33	
1.05_0.6	616	18.47		675	10.97	
1.05_0.7	645.5	17.27	×	701	8.17	
1.1_0.5	587	18.77		520	12.73	
1.1_0.6	659	10.5		692.5	10.07	
1.1_0.7	680.5	10.07	×	713.5	7.4	×
1.15_0.5	588.5	18.37		687.5	9.5	
1.15_0.6	619.5	17.93		702.5	8.93	
1.15_0.7	680	10.13	×	720	7.13	×

Tips: The "×" part of the table represents segregation of self-compacting concrete.

In the anti-segregation performance of the two aggregates in the same volume of water-cement ratio under the influence of superplasticizer dosage is greater. When the superplasticizer dosage reaches 0.7%, serious segregation phenomenon generally occurs in the two groups of experimental tests. After selecting the basic water-cement ratio, the reasonable superplasticizer is the key to prevent segregation.

3.2 Modelling of Paste Threshold Calculation for Magnetite Self-compacting Concrete

Extensibility and T_{200} measurements were carried out for the mix ratios given in Table 1, and the yield strength and bond strength of each group of paste were calculated according to the theoretical equations of Zhang [8], and the results are shown in Table 4. For the test results three times spline interpolation method was carried out with a step size of 0.01, then the SCP Zone was obtained.

According to the specification [17], it is known that good self-compacting concrete extension should be greater than 600mm and T500 should be between 5-20s. Tests according to the above test method for paste can give the magnetite self-compacting concrete zone (SCC Zone) as shown in Fig. 4.

(a) 1.15_0.5 (b)1.15_0.5

Fig. 3. Comparative experiment of concrete:(a)magnetite concrete (b)original concrete

Table 4. Results of mini-slump flow tests, rheological characteristics, and thresholds of paste for Zhang's model.

Number	T_{200}(s)	$\tau_{threshold}$(Pa)	$\eta_{threshold}$(Pa·s)	τ_{paste}(Pa)	η_{paste}(Pa·s)
1_0.5	1.97	0.52/0.64	11.71/34.71	0.69	23.14
1_0.6	1.80	0.52/0.64	11.73 /34.74	0.53	21.17
1_0.7	1.33	0.52/0.64	11.75/34.77	0.36	15.67
1.1_0.5	1.27	0.51/0.63	12.27/35.27	0.37	14.55
1.1_0.6	1.20	0.51/0.63	12.29/35.30	0.33	13.77
1.1_0.7	1.07	0.51/0.63	12.31/35.33	0.29	12.23
1.2_0.5	1.05	0.51/0.63	12.78/35.78	0.19	11.79
1.2_0.6	1.00	0.51/0.63	12.79/35.81	0.16	11.22
1.2_0.7	0.73	0.51/0.63	12.81/35.83	0.15	8.22

The test results show that the yield strength and bond strength thresholds of the paste increased significantly when larger specific gravity aggregate was used, i.e., the threshold model suggests that it is easier for concrete to obtain a larger fluidity, but places higher demands on the anti-segregation properties, as shown in Table 4. From the equation proposed by Zhang [8], $\Delta\rho$ responds to the difference in density between coarse aggregate and mortar, as the density of coarse aggregate rises it may appear that the coarse aggregate produces more subsidence than the mortar thus leading to the separation of aggregate from the paste, resulting in segregation. All the bond strength thresholds in Table 4 are greater than the bond strength thresholds of the paste, indicating that there is no paste self-compacting (SCP) zone, and all the concretes will suffer from segregation. However, from the test results of the concrete, there was no large area of segregation and the prediction was inaccurate. The reason may be that the mortar has good bonding performance under reasonable water reducing agent dosage, and there is good holding force between aggregate and mortar, which provides resistance to the sinking of aggregate and hinders the sinking of aggregate. However, when the superplasticizer is mixed with more, the bonding force of the mortar decreases, no longer able to block the sinking of coarse aggregate, so the phenomenon of segregation occurs. For the bonding performance of mortar should be considered in the formula, for this, the mortar bonding coefficient β_ρ is introduced. $\Delta\rho$ is calculated in the following equation 1, where the value of β_ρ is determined by test according to the density of different aggregates. The value of β_ρ in this test is taken as 1.41.

$$\Delta\rho = \rho_{CA} - \beta_\rho * \rho_{mortar} \tag{1}$$

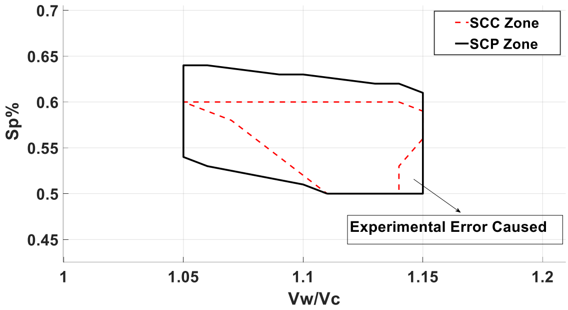


Fig. 4. Correction model validation

The concrete tests show that the addition of heavy aggregates to the concrete flowability compared to ordinary aggregates appears to be significantly reduced, in the paste test, the yield strength threshold of the paste should correspondingly decline, that is, the yield strength of the paste should not be easy to satisfy the threshold requirements, but the prediction results of the paste is contrary to it. Therefore, a correction factor β_s for the yield strength threshold of magnetite is introduced, with the aim of considering the discounting of concrete flow by aggregates with larger specific gravity such as magnetite. The corrected equation is shown in Eq. 2, and the value of β_s is taken as 0.81.

$$\tau_{\text{paste, threshold}} = \beta_s \frac{\rho_{\text{mortar}}\, g(b+2\delta_{\text{mortar}})^2}{2(a+2\delta_{\text{mortar}})}(1-\phi/\phi_{max})^n \tag{2}$$

The results of the validation are shown in Fig.4, in which there is a good overlap between the paste self-compacting region and the concrete self-compacting region, in which the concrete self-compacting region containing magnetite is completely surrounded by the paste self-compacting region, and the model has a good accuracy. The non-overlapping part of the figure may be caused by the discrete error of the concrete test.

4 Conclusions

Study on the paste threshold for the flowability of magnetite self-compacting concrete was carried out through tests, and the following conclusions were drawn:

(1) Relative to ordinary aggregates, the flow of magnetite aggregate concrete decreases by about 10% and is prone to segregation, which can be avoided by adjusting the superplasticizer dosage.

(2) Based on the test data of magnetite aggregate concrete, the mortar bond coefficient β_ρ and the yield strength reduction coefficient β_s were introduced, and the

calculation model of the paste threshold for the flowability of magnetite self-compacting concrete was established.

Acknowledgments

The research was supported by the National Natural Science Foundation of China (No. 52079047), the National Key Research and Development Program of China (No.2017YFC0404902) and the Postgraduate Research and Practice Innovation Program of Jiangsu Province (No. SJCX23_0192). The authors gratefully acknowledge the financial support.

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