Study on the bulk density and influencing factors of green ferronickel slag self-compacting concrete aggregates

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Abstract. The compactness of aggregates has a significant impact on the workability of self-compacting concrete. The bulk density of aggregates is an effective parameter for evaluating the compactness of aggregates, reflecting the degree of compactness of the aggregate system. This study aims to explore the theoretical calculation model and application of the bulk density of green ferronickel slag as aggregates in self-compacting concrete. The influence of different particle size distributions and ferronickel slag content on the bulk density of the aggregate system was analyzed. Based on the calculation method of the maximum bulk density of aggregates, the bulk density of the aggregate system was calculated for different particle size distributions and nickel-iron slag content, and the effect of nickel-iron slag content on the compactness of the aggregate system was analyzed.

Keywords: self-compacting concrete; aggregates; bulk density; particle size distribution; ferronickel slag.

1. Introduction

Self-compacting concrete (SCC) is widely used in modern infrastructure construction due to its high fluidity, self-leveling ability, and compactness. However, achieving good workability often requires a high amount of cementitious materials, leading to increased carbon emissions [1,2]. Reducing cementitious materials while maintaining performance is crucial for high-quality civil engineering. Controlling SCC's rheological properties and studying the correlation between mortar performance and SCC properties are important research directions.

The demand for aggregates in concrete is substantial, causing environmental impacts from excessive natural aggregate mining. Industrialization has resulted in increased solid waste generation, burdening the environment [3,4]. Landfilling such waste, including ferronickel slag (FNS) from nickel-iron alloy smelting, poses safety and environmental hazards due to harmful heavy metal ions. Utilizing FNS as concrete aggregates can improve strength and prevent the leaching of heavy metal ions, benefiting the environment and human health. Investigating FNS-based aggregate bulk density in SCC and its impact on aggregate system compactness is vital for addressing pollution and carbon emissions in infrastructure construction.

2. Theoretical and calculation models of aggregate compactness

The bulk density of aggregate particles can greatly optimize the mix design of concrete [5], so studying the compactness of aggregate particles is of great significance. Firstly, using aggregates with maximum bulk density can significantly reduce the number of cementitious materials in concrete, as less cementitious material is needed to fill the gaps between aggregate particles. Since cementitious materials are typically the more expensive components of concrete, optimizing the compactness of aggregate particles can not only reduce the economic cost of concrete but also reduce its environmental impact. In addition, excessive use of cementitious materials can also cause concrete to experience drying shrinkage, cracking, and durability problems. Therefore, optimizing the compactness of aggregate particles can improve the performance of concrete and save costs.

Secondly, the morphological characteristics of aggregates, such as shape, surface texture, and size, can be uniformly described by the parameter of particle compactness. Therefore, the characteristics of complex aggregates can be characterized by a single parameter, which is extremely helpful for selecting aggregates in actual concrete production scenarios. By measuring the bulk density of aggregates, their properties can be quantified, and the mix design of concrete can be adjusted accordingly, thus achieving the optimal performance of concrete. Therefore, studying the influence of aggregate compactness on the properties of concrete and optimizing aggregate compactness is one of the main research directions for optimizing the mix design of concrete.

2.1 Theoretical research on aggregate compactness

The geometric characteristics of solid aggregates such as shape, material and particle size distribution can affect their pile compactness, which can be used as a general indicator of the geometric characteristics of aggregates. Aggregate pile compactness is defined as the ratio of absolute volume of aggregate to pile volume or the ratio of pile density to apparent density in unit volume space, and can be expressed by **Eq. (1)**:

$$\gamma = \frac{V_1}{V_2} = \frac{\rho_2}{\rho_1} \tag{1}$$

Where, γ represents the compactness of the solid particle packing, V_1 and V_2 represent the absolute volume and bulk volume of the particles, respectively, and ρ_1 and ρ_2 represent the apparent density and bulk density of the particles, respectively.

From a theoretical perspective, when the compactness of the aggregate reaches 1, it means that the aggregate has been packed into a dense solid. However, in practical production, the compactness of the aggregate cannot reach this theoretical value. Nevertheless, by optimizing the packing of the aggregate, the compactness of the aggregate can be maximized. The compactness of the aggregate is greatly influenced by factors such as particle size, particle shape, and packing method.

In concrete systems, the packing of mixed aggregates can usually be divided into two categories [6]: (1) In this case, if large particle aggregates dominate, the compactness of the entire aggregate can be represented by the compactness of the large particle aggregates. If small particle aggregates dominate, the compactness of the entire aggregate can be represented by the compactness of the small particle aggregates. (2) Mixed particle systems with interactive effects. In this case, when a small amount of small particle aggregates are included in a large number of large particle aggregates, if the size of the small particle aggregates is larger than the gap between the larger particle aggregates, a loosening effect (Fig. 1) will occur, which will cause the larger-sized aggregate particles to disperse, thereby reducing the compactness. When a small amount of larger particle aggregates are included in a small particle system, new gaps will be formed between the small particle aggregates packed near the larger particle aggregates, resulting in a wall effect (Fig 2). The interaction effects between all particles will reduce the compactness of the entire particle system.

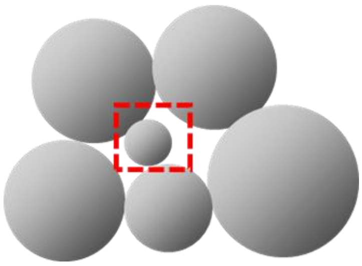

Fig. 1 Loosening effect

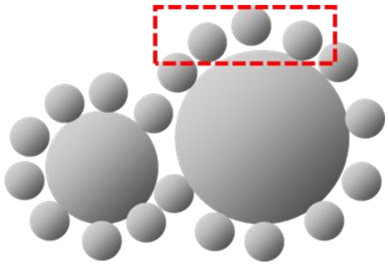

Fig. 2 Wall effect

2.2 Calculation model of aggregate compactness

In terms of calculation models for the compactness of particle systems, some scholars have conducted research. Among them, the French Road and Bridge Testing Center [7] proposed a compressible packing model, which systematically considers the influencing factors when different quantities and sizes of particles are mixed together. This model has been widely recognized by researchers in the field of concrete aggregates. The model mainly considers the following three parameters:

(1) Compactness of single-sized particles;

(2) Grading of mixed particle systems with different sizes;

(3) Compaction conditions.

In order to computationally calculate the compactness of aggregates, the model proposes the concepts of virtual compactness and residual compactness. Virtual compactness refers to the maximum compactness that can be achieved when particles of different sizes are mixed together, denoted by the symbol γ_i. Residual compactness refers to the maximum compactness that can be achieved when particles of the same size are mixed together, denoted by the symbol β_i.

It can be concluded that particle packing situations can be divided into mixed particle systems with no interactive effects and mixed particle systems with interactive effects. The CPM model has different calculation formulas based on different packing situations. When the particle pile belongs to the mixed particle system without interaction, the denseness of the binary mixed particle pile dominated by large particle size is expressed by **Eq. (2)**:

$$\gamma = \gamma_1 = \frac{\beta_1}{1-y_2} \tag{2}$$

The densities of the binary mixed particle pile dominated by small particle size are expressed by **Eq. (3)** [6]:

$$\gamma = \gamma_2 = \frac{\beta_2}{1-(1-\beta_2)y_1} \tag{3}$$

Where, y_1 and y_2 express the volume content of large particle size and small particle size, respectively.

When it is difficult to accurately determine which particle size dominates the mixed particle system with no interactive effects, use equations (2) and (3) to calculate γ_1 and γ_2, and γ take the smaller value between γ_1 and γ_2. When there are multiple different particle sizes in a mixed particle system with no interactive effects and each particle size differs greatly, the calculation formula for the compactness of multivariate particle packing can be obtained as **Eq. (4)**:

$$\gamma = \gamma_i = \frac{\beta_i}{1-(1-\beta_i)\sum_{j=1}^{i-1} y_j - \sum_{j=i+1}^{n} y_j} \tag{4}$$

$$\gamma = \min_{1 \le i \le n} \gamma_i \tag{5}$$

Where γ_i represents the virtual stacking compactness when class *i* particles dominate, y_i expresses the volume fraction of particles with particle size d_i, and d_1, d_2, d_3, d_n, d_i are calculated by **Eq. (6)** and the virtual stacking compactness of the multiparticle mixture is obtained by **Eq. (5)**.

$$\log_{10}(d_i) = [\log_{10}(d_{\max}) + \log_{10}(d_{\min})]/2 \tag{6}$$

However, the actual aggregate packing situation in concrete belongs to a mixed particle system with interactive effects, and the previously mentioned loosening effect and wall effect will occur, resulting in differences in the formula for calculating the compactness of the particle system. The effects of the loosening effect and wall effect on the compactness of the particle system are expressed by coefficients a_{ij} and b_{ij}, respectively. After a large number of experiments to obtain the value of these two factors **Eq. (7)** and **(8)**:

$$a_{ij}=\sqrt{1-\left(1-\frac{d_j}{d_i}\right)^{1.02}} \qquad \text{当} d_j \le d_i \tag{7}$$

$$b_{ij}=\sqrt{1-\left(1-\frac{d_i}{d_j}\right)^{1.50}} \qquad \text{当} d_i \le d_j \tag{8}$$

Where d_i and d_j are the diameters of the particles of class *i* and *j*, respectively. Substituting the loosening effect coefficient and the vessel wall effect coefficient, the virtual stacking compactness equation for the binary particle system with interaction is obtained:

When the large-size particles dominate, the stacking compactness equation is revised to **Eq. (9)**:

$$\gamma=\gamma_1=\frac{\beta_1}{1\text{-}\left(1-\frac{a_{12}\beta_1}{\beta_2}\right)y_2} \tag{9}$$

When small size particles dominate, the stacking compactness equation is revised to **Eq (10)**:

$$\gamma=\gamma_2=\frac{\beta_2}{1\text{-}\left(1-\beta_2+b_{21}\beta_2\left(1-\frac{1}{\beta_1}\right)\right)y_1} \tag{10}$$

To ensure that concrete has good fluidity, the actual aggregate in concrete is a multivariate particle size mixed system. The formula for the virtual compactness of the multivariate system is derived from the formula for the virtual compactness of the binary particle system and is represented by **Eq (11)**. At the same time, the virtual stacking compactness of the multivariate system needs to satisfy **Eq. (5)**

$$\gamma_i=\frac{\beta_i}{1-\sum_{j=1}^{i-1}\left[1-\beta_i+b_{ij}\beta_i\left(1-\frac{1}{\beta_j}\right)\right]y_i-\sum_{j=i+1}^{n}\left(1-\frac{a_{ij}\beta_i}{\beta_j}\right)y_j} \tag{11}$$

The above virtual compactness is based on the actual pile compactness calculation of single particle size, and the calculated results only express the simulated value of the ideal pile compactness when multiple particle sizes with different volume ratios, which is still different from the actual compactness and needs further exploration of the relationship between the actual compactness and the virtual compactness. De. Larrard. F [8] also considered that the compaction method also affects compactness, so he proposed the compaction index K to represent the degree of compaction during aggregate packing. The relationship between the virtual compactness and the actual compactness is established using the compaction index K, and **Eq. (12)** [8] is established:

$$K=\sum_{i=1}^{n}K_i=\sum_{i=1}^{n}\frac{y_i/\beta_i}{1/\alpha_t-1/\gamma_t} \tag{12}$$

Where α_t represents the actual compactness.

The compaction index K represents the compression effect during aggregate packing. The larger the K, the better the compaction degree during mixing of the aggregate, and the closer the actual compactness is to the ideal compactness. That is, when K tends to infinity, the actual compactness approaches the virtual compactness infinitely. The results are as demonstrated in the literature.

3. Influence of coarse aggregate particle size ratio on stacking compactness

According to the characteristics of self-compacting concrete, coarse aggregates with particle sizes below 20 mm are generally selected to better ensure the workability of self-compacting concrete. According to the Chinese national standard GB/T 14685-2011, coarse aggregates with particle sizes below 20 mm are generally divided into three size intervals: 4.75-9.50 mm, 9.50-16 mm, and 16-19 mm. Based on this, this study mainly investigates the influence of grading combinations of these three intervals on the compactness of aggregate packing. Basalt and nickel-iron slag coarse aggregates were sieved into these three particle size intervals using standard sieves, and the actual compactness of single particle size intervals was measured first (Table 1).

Table 1. Compaction indices without stacking method

Particle size range (mm)	0%	10%	20%
4.75-9.5	0.7114	0.7389	0.7150
9.5-16.0	0.6869	0.6921	0.6890
16.0-19.0	0.6981	0.6980	0.6995

Then the test values of pile compactness of coarse aggregates composed of different particle size ratios are measured, and the actual pile compactness is calculated according to Eq. (12). The compaction index K chosen for the calculation of pile compactness is 4.1, and the results are shown in Table 2.

Table 2. The compactness of coarse aggregate pile with different grading

Volume content of particles in each particle size interval (V %)			Accumulation density	
4.75-9.5 mm	9.5-16.0 mm	16.0-19.0 mm	Virtual pile compactness	Actual pile compactness
10	30	60	0.735	0.596
20	20	60	0.757	0.610
30	10	60	0.775	0.620
10	40	50	0.730	0.595
20	30	50	0.752	0.609
30	20	50	0.769	0.620
40	10	50	0.764	0.625
10	50	40	0.725	0.592
20	40	40	0.747	0.607
30	30	40	0.764	0.617
40	20	40	0.759	0.622
50	10	40	0.754	0.622
10	60	30	0.720	0.587
20	50	30	0.742	0.602
30	40	30	0.758	0.612
40	30	30	0.754	0.618
50	20	30	0.749	0.618
60	10	30	0.744	0.614

According to Table 2, the maximum actual compactness calculated by the CPM model is 0.625, with 40%, 10%, and 50% of aggregates in the 4.75-9.5 mm, 9.5-16 mm, and 16-19 mm size intervals, respectively. The study found that the virtual compactness was calculated based on the dominant particle size interval of 4.75-9.5 mm for the 10 mixes with the maximum actual compactness. When the content of aggregate in the 4.75-9.5 mm size interval was greater than 30%, the actual compactness was larger, and the maximum value was obtained when the content was 40%. The study also found that the actual compactness of the aggregate increased with the increase of the content of the 4.75-9.5 mm size interval. In addition, the maximum actual compactness increased with the increase of the content of the 16-19 mm size interval. When the content of the 16-19 mm size interval was fixed, the actual compactness of the coarse aggregate system tended to increase with the decrease of the content of the 9.5-16 mm size interval, but there might be a slight decrease in actual compactness when the content decreased from 20% to 10%. Therefore, the optimal content of the 9.5-16 mm size interval was 20%.

4. Influence of ferronickel slag aggregate admixture on pile compactness

Based on the research results of the coarse aggregate compactness under different gradations, the largest eight aggregate gradations with compactness were selected, and the compactness was calculated by replacing 10% and 20% of the coarse aggregates with nickel-iron slag in the 4.75-9.50 mm, 9.5-16.0 mm, and 16.0-19.0 mm size intervals respectively (Table 3). It was found that with the increase of nickel-iron slag content, the actual compactness of the coarse aggregate system first increased and then decreased, and the actual compactness was the highest when the content was 10%. When the nickel-iron slag content increased from 0% to 10%, the compactness of the single particle size aggregates in the 4.75-9.5 mm and 9.5-16 mm size intervals increased significantly, while the compactness of the single particle size aggregates in the 16-19 mm size interval was less affected. This may be because the fineness of the nickel-iron slag aggregates in the 4.75-9.5 mm and 9.5-16 mm size intervals is lower than that of the basalt aggregates, which can fill some of the voids in the mixed aggregates. Overall, adding 10% nickel-iron slag can improve the actual compactness of the entire aggregate system. However, when the nickel-iron slag content increased from 10% to 20%, the compactness of all three single particle size aggregate systems decreased, but they were still higher than the actual compactness without nickel-iron slag, indicating that adding nickel-iron slag can increase the maximum compactness of the aggregates. However, excessive addition of nickel-iron slag aggregates, which have a multi-angular shape, can increase the voids in the aggregate system [9].

Table 3. Coarse aggregate pile compactness with different ferronickel slag admixture

No	Volume content of particles in each particle size interval (%)			Virtual pile compactness			Actual pile compactness		
	4.75-9.5 mm	9.5-16.0 mm	16.0-19.0 mm	0% FNS	10% FNS	20% FNS	0% FNS	10% FNS	20% FNS
D1	30	10	60	0.775	0.781	0.777	0.620	0.624	0.623
D2	30	20	50	0.769	0.776	0.771	0.620	0.625	0.621
D3	40	10	50	0.764	0.773	0.767	0.625	0.631	0.627
D4	30	30	40	0.764	0.771	0.766	0.617	0.623	0.622
D5	40	20	40	0.759	0.768	0.761	0.622	0.629	0.625
D6	50	10	40	0.754	0.764	0.757	0.622	0.630	0.624
D7	40	30	30	0.754	0.763	0.756	0.618	0.625	0.621
D8	50	20	30	0.749	0.759	0.751	0.618	0.627	0.621

5. Conclusion

(1) We used a theoretical model to calculate aggregate bulk density with different particle size distributions. The actual bulk density of the aggregate system first increased and then decreased as the proportion of 4.75-9.5 mm aggregates increased. The highest bulk density was achieved at a 40% proportion of 4.75-9.5 mm aggregates.

(2) We studied the impact of different proportions of nickel-iron slag on aggregate bulk density. Adding nickel-iron slag to replace coarse aggregates increased the bulk density for the same particle size distribution. The maximum bulk density occurred at a 10% proportion of nickel-iron slag. Smaller particle size of the slag in the 4.75-9.5 mm and 9.5-16 mm ranges filled some voids, contributing to the increased density. However, excessive nickel-iron slag addition led to increased voids and decreased bulk density.

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