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Experimental Research on Mix Proportions of Reactive Powder Concrete Containing Steel Slag Powders

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Abstract: *Steel slag powders were compared with cement in terms of chemical and mineral compositions. Then, steel slag powders with chemical compositions similar to cement and physico-mechanical properties meeting requirements were used as active components to completely replace cement to design mix proportions of reactive powder concrete (RPC) containing steel slag powders. According to the preparation principle of RPC, the benchmark mix proportions were proposed. By studying influences of various compositions of RPC containing steel slag powders on the properties and changes in the properties, the reasonable mix proportions of various compositions of RPC containing steel slag powders were obtained. The research provides important reference for the preparation and application of RPC in which cement is replaced with steel slag powders.*

Keywords: *steel slag powder, cement, mix proportion, reactive powder concrete*

1. Introduction

Reactive powder concrete (RPC) is a novel cement-based composite of ultrahigh strength, excellent durability, and broad application prospect [1]. The reactive powders mainly include cement, silica fumes, and quartz powders. The increase in the cement content may give rise to problems including the rising hydration heat of RPC, enlarged thermal contraction and self-contraction, and increased cost and energy consumption, which seriously hinder the popularization and application of RPC. Search and use of reactive materials that meet the preparation principle and have extensive sources have been the key to RPC research.

Steel slags are by-products produced for removing impurities in steel in the steelmaking process. Preparing RPC using steel slags has been studied in China and abroad, in which steel slags are mainly used as concrete aggregates. Some research also provides the example of using steel slags to partially replace cement as the additives of concrete [2]. However, using steel slags as the cementing material to prepare RPC is seldom reported in China and abroad. The current research experimentally studied preparation of RPC containing steel slag powders according to the preparation mechanism and principle of RPC and combining with existing research findings.

2. Main raw materials

2.1 Cement and steel slags

Different varieties and types of cement differ greatly in properties, so the selection of cement types is vital for the preparation of high-strength concrete. P.O 42.5 ordinary Portland cement with the specific surface area of 366 m2/kg produced by a cement plant in Shandong Province, China was used. The specific surface area of steel slag powders was 442 m2/kg. Chemical compositions of cement and steel slags are shown in Table 1.

Table 1: Main chemical compositions of cement and steel slag powders

Chemical compositions	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O	P_2O_5	TiO_2	K_2O
Proportions in cement/%	64.95	21.65	3.66	3.87	2.01	0.58	0.08	-	0.29	0.77
Proportions in steel slags/%	50.5	21.32	10.16	7.01	4.06	3.6	0.29	0.8	0.62	0.51

As displayed in Table 1, the chemical compositions of steel slag powders resemble those of cement. The mineral compositions of steel slags are mainly determined by the alkalinity of steel slags. The higher the alkalinity is, the greater the activity [3]. The alkalinity of steel slags is m(CaO)/m(SiO2+ P2O5) = 2.3>1.8, so they belong to high-alkalinity steel slags.

2.2 Silica fumes

Silica fumes used in the experiments contained as much as 92% of SiO2, and their average particle size was 0.13 μm. The silica fumes are spherical, so they play a favorable lubrication effect. According to previous research [4], silica fumes have the best filling effect and undergo secondary hydration with cement-hydrate Ca(OH)2 to the most extent at the same time when the ratio of silica fumes to cement is 0.25.

2.3 Quartz sand and quartz powders

Quartz sand which mainly functions as main aggregates in RPC has the particle size in the range of 0.16 ~ 0.60 μm. The SiO2 content is not lower than 99% in the mineral compositions. The specific surface area of quartz powders is 519 m2/kg.

2.4 Water reducer

The water-reducing rate of water reducers is the decisive factor for the strength of RPC [5]. The water reducer used in the experiment was a polycarboxylate superplasticizer produced by Shandong Boke Chemicals Stock Co., Ltd.

3. Experimental methods

3.1 Sample preparation

1) After being weighed according to the proportions, various solid raw materials were poured in a planetary cement mortar mixer for dry mixing at first for 3 min at a slow rate. Then, the mixing was stopped to add the water reducer and water, followed by slow stirring for 3 min and then fast stirring for 5 min.

2) The stirred mixture was poured in a triplet mold of cement mortar measuring 40 × 40 × 160 mm3, which was then vibrated and molded on a shaking table for cement mortar.

3) After molding, the sample was placed in a standard curing box to be cured for 24 h. After being demolded, the sample was put in a concrete quick curing box for corresponding thermal curing. The cured sample was slowly cooled to the room temperature and then its strength was tested.

3.2 Performance tests

The fluidity and compressive strength of the mortar were taken as the performance parameters for testing RPC. The jumping table method stipulated in the Test method for fluidity of cement mortar (GB/T2419-2005) was used to measure the fluidity of RPC. The strength was tested following the standard GB/T17671-2021.

4. Experimental results and analysis

To verify the performance of RPC containing steel slag powders, the ratio of cement (steel slags): silica fumes: ground quartz powders of 1：0.25：0.37 was taken as the benchmark mix proportion. The mix proportions of cement-based RPC and RPC containing steel slag powders were designed from the water-binder ratio, mixing amounts of superplasticizer, silica fumes, and quartz powders, and sand-binder ratio. The ranges of mix proportions of various raw materials of the RPC containing steel slag powders were determined.

4.1 Influences of the water-binder ratio on performance of RPC

Because the maximum particle size and proportion of aggregates both reduce, aggregates become a disperse phase with improved homogeneity in concrete. Therefore, the quality of mortar directly determines the performance of concrete. In the experiments, the mix proportion of the water reducer was 1.5%, and the water-binder ratio was increased from 0.18 to 0.24, with an interval of 0.02. Figure. 1 and Figure. 2 separately show influences of the water-binder ratio on the fluidity and compressive strength of RPC.

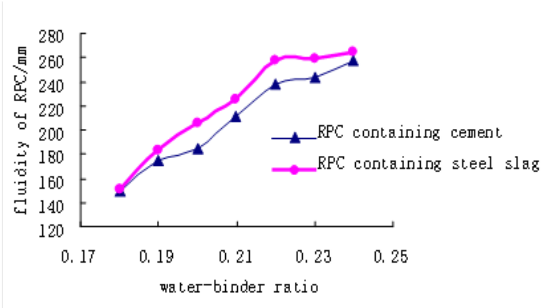

Figure 1: Influences of changes in the water-binder ratio on fluidity of RPC

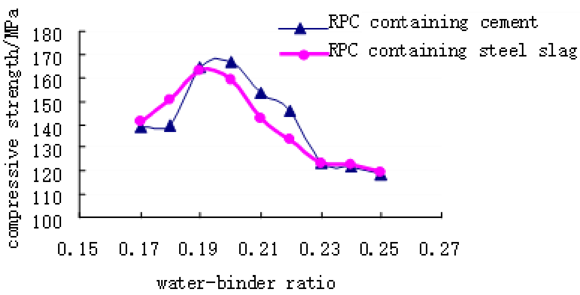

Figure 2: Influences of changes in the water-binder ratio on compressive strength of RPC

It can be seen from Fig. 1 that changes in the fluidity of RPC with the water-binder ratio follow the general law. Under conditions of the same water-binder ratio, steel slag powders have higher fluidity than cement because the lubrication effect of steel slag powders improves the fluidity of RPC.

As shown in Fig. 2, the compressive strength of RPC has a peak when it changes with the water-binder ratio, which is not completely similar to the ordinary concrete. This is because when the water-binder ratio is too large, voids are formed in hardened RPC, which affects the compactness of RPC; if the water-binder ratio is too small, the cementing material may not be completely hydrated, thus affecting the strength.

By comprehensively considering the strength and workability of RPC, the optimal water-binder ratio of RPC containing steel slag powders is in the range of 0.18 ~ 0.20 under conditions of the raw materials and process used in the experiments.

4.2 Influences of the sand-binder ratio on performance of RPC

For ordinary concrete, the amount of cement mortar in the mixture is relatively insufficient with the increase in the sand ratio, thus weakening the lubrication effect of cement mortar on the sand and reducing the fluidity of the mixture. However, if the sand ratio is too low, it cannot guarantee that there is an enough mortar layer between aggregates, which weakens the lubrication effect of the mortar on coarse aggregates and also decreases fluidity of the mixture. Because there are no coarse aggregates in the RPC, only the lubrication effect of mortar on fine aggregates of the prepared RPC is considered. That

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is to say, the sand-binder ratio should be considered under conditions of the same water-binder ratio. In the experiments, the water-binder ratio was 0.19, mix proportion of water reducer was 1.5%, and mixing amount of quartz sand was in the range from 0.8 to 1.4. Influences of the sand-binder ratio on the fluidity and compressive strength of RPC mortar are shown in Figure. 3 and Figure.4.

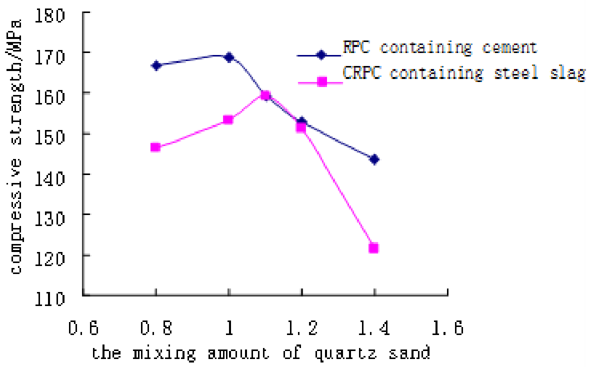

Figure 3: Influences of changes in the mixing amount of quartz sand on fluidity of RPC

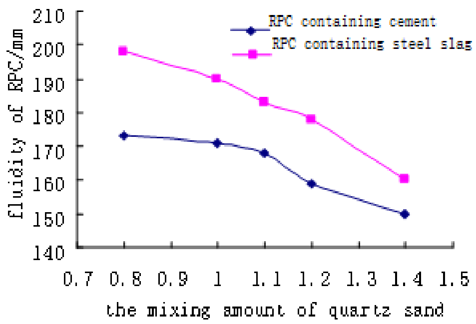

Figure 4: Influences of changes in the mixing amount of quartz sand on compressive strength of RPC

It can be seen from Figs. 3 and 4 that the sand-binder ratio exerts great influences on the fluidity of RPC. As the sand-binder ratio grows, the fluidity of the mixture reduces. When the sand-binder ratio is lower than 1.1, its influence on the fluidity is not obvious while the compressive strength gradually rises. When the sand-binder ratio is 1.1, the compressive strength reaches 159.21 MPa, which is approximate to that of cement-based RPC. However, as the mixing amount of quartz sand increases, the RPC mixture is found to have rapidly decreased fluidity and the compressive strength also plummets to 121.2 MPa. This is mainly because as the mixing amount of quartz sand grows, the fluidity of RPC mixture reduces, and it is difficult to vibrate and compact the molded samples. Besides, because the mortar layer on the aggregates becomes thinner, the compressive strength of the RPC sample decreases abruptly.

Through comprehensive consideration, the optimal sand-binder ratio of RPC containing steel slag powders should be in the range of 1.0 ~ 1.2.

4.3 Influences of mixing amounts of silica fumes and quartz powders on performance of RPC

The strength of RPC is mainly contributed by the cement hydration, pozzolanic effect of silica fumes, micro-aggregate effect of quartz powders at the room temperature, and pozzolanic effect of quartz powders at the high temperature [6]. The total mixing amount of silica fumes and quartz powders was fixed as 0.62. Influences of changes in the adding amount of silica fumes and quartz powders on the compressive strength and fluidity of RPC were observed by changing the adding amount of silica fumes. The contents of silica fumes were 0.2, 0.25, 0.3, 0.35, and 0.4. Influences of the mixing amount of silica fumes and quartz powders on performance of RPC are illustrated in Figure. 5 and Figure.6.

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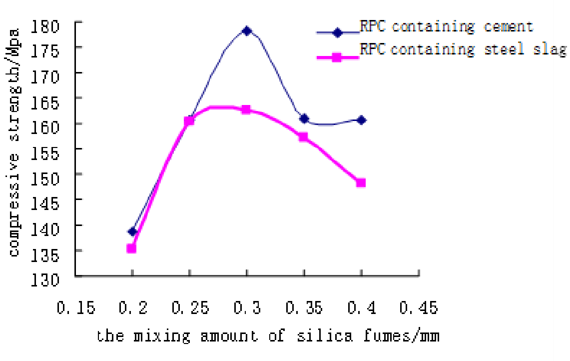

Figure 5: Influences of changes in the mixing amount of silica fumes on compressive strength of RPC

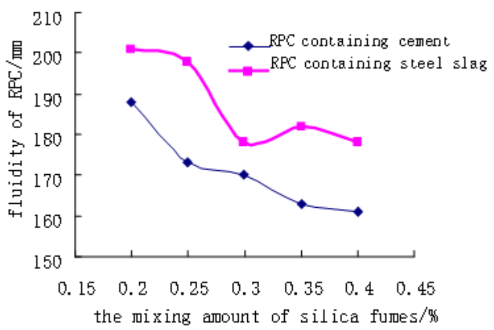

Figure 6: Influences of changes in the mixing amount of silica fumes on fluidity of RPC

As shown in Fig. 5, when the total amount of silica fumes and quartz powders was fixed to be 0.62 and the water-binder ratio remains unchanged, the strength of RPC first increases and then decreases. When the mixing amount of silica fumes is 0.3, the strengths of cement-based RPC and RPC containing steel slag powders both reach the maximum: 162.40 MPa for RPC containing steel slag powders and 178.20 MPa for cement-based RPC.

It can be seen from Fig. 6 that as the mixing amount of silica fumes grows, the fluidity of RPC reduces. This is probably because the content of fine powders enlarges in the powders with the growing silica fumes, so the specific surface area of the material enlarges, which calls for a larger amount of water and corresponding reduces the fluidity.

4.4 Influences of the mixing amount of the superplasticizer

Superplasticizer is one of the essential compositions to prepare high-performance concrete. It not only imparts the needed workability to concrete at a low water-binder ratio, but also can improve the performance of hardened concrete. In the experiments, the benchmark mix proportion of 0.19 was used for the water-binder ratio, and the mixing amount of the superplasticizer was set in the range of 1% to 4%, with an interval of 0.5%. Influences of the superplasticizer on the fluidity and strength of RPC are displayed in Figure. 7 and Figure.8.

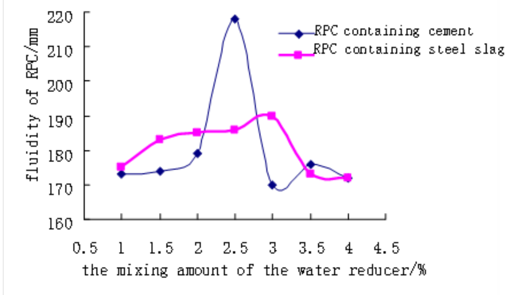

Figure 7: Influences of changes in the mixing amount of the water reducer on fluidity of RPC

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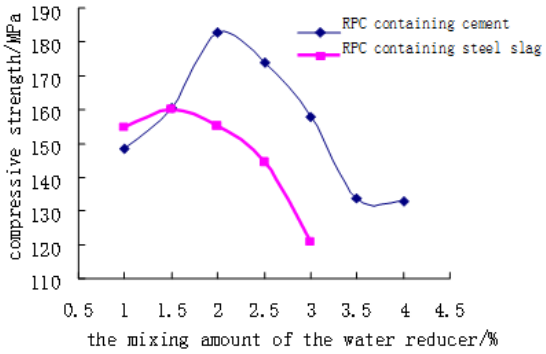

Figure 8: Influences of changes in the mixing amount of the water reducer on compressive strength of RPC

The superplasticizer also has saturability for RPC containing steel slag powders. It can be seen from Fig. 7 that the fluidity of RPC containing steel slag powders reaches the maximum when the mixing amount of the superplasticizer reaches 3%. Then, the mortar becomes increasingly thick with the growing mixing amount of the superplasticizer, so that bubbles therein find them difficult to escape, so the fluidity decreases.

As displayed in Fig. 8, the compressive strength of RPC increases at first and then decreases with the increment in the mixing amount of the superplasticizer. This indicates that RPC does not have good fluidity either the mixing amount of the superplasticizer is too small or too large. The poor fluidity causes low workability and affects the strength of RPC. The compressive strength of RPC containing steel slag powders is the maximum (160.15 MPa) when the mixing amount of the superplasticizer is 1.5%; that of the cement-based RPC is maximum (182.89 MPa) when the mixing amount is 2.0%.

By comprehensively considering the strength and workability of RPC, it is suggested to set the optimal mixing amount of the superplasticizer powders as 1.5% ~ 2.5% when preparing RPC containing steel slag.

5. Conclusions

Combining with the design of mix proportions of cement-based RPC, steel slag powders with chemical compositions similar to cement and cementitious reactivity lower than cement were used to replace cement as the cementing material to prepare RPC. By adjusting the mix proportions of raw materials of RPC, high-strength RPC containing steel slag powders was prepared. The research provides important reference for the preparation and application of RPC containing steel slag powders. The following conclusions are obtained through experiments:

1) Analysis of compositions of steel slag powders reveals that the steel slag powders have similar chemical compositions with cement clinker and potential cementitious reactivity, so they can replace cement as the cementing material.

2) By comprehensively considering the strength and workability of RPC, the ranges of mix proportions of various raw materials for preparing RPC containing steel slag powders were obtained as follows: water-binder ratio: sand-binder ratio: silica fumes: water reducer = (0.18 ~ 0.2): (1.0 ~ 1.2): (0.25 ~ 0.3): (1.5% ~ 2.5%).

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