Effect of slag powder on strength development of alkali-activated recycled cement

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Abstract. The effect slag powder on strength development of alkali-activated recycled cement paste was investigated. The results show that alkali-activated recycled cement paste has low cementing strengths, which depend on the types of the original cement. The alkali-activated recycled cement pastes prepared from the recycled cement pastes with the original cement of fly ash cement (PF) resulted the highest strengths, followed by that from slag cement, and that from the ordinary Portland cement resulted the lowest strengths. Replacing recycled cement pastes partly by slag powder can greatly increase the strengths of alkali-activated recycled cement pastes. The 90 day flexural and compressive of alkali-activated recycled PF replaced by 30% slag powder were 6.7MPa and 51.9 MPa. Scanning electron microscopy(SEM) indicated that the microstructure of the alkali-activated recycled cement paste with 30% replacement by slag powder is much denser than that without replacement.

1. Introduction
Construction wastes have already exceeded 15 billion tons annually in china, which accounted for 40% of urban landfill. Efforts have been made to make use of waste concrete, mostly are to be used as recycled aggregate for concrete[1-3]. However, the lower strength and higher water requirement have restricted its effective application. And the more, the waste hardened cement paste separated from the waste concretes have not found an effective way for application yet. Some researchers[4-7] tried to make use of waste concrete powders as a kind of active mineral admixtures for cement or concrete, however, it turned out that it severely reduces the performance of the cement and concrete. Gong and Miao[8-9] found that hardened cement pastes from recycled waste concrete can be used to preparing alkali-activated recycled cement, using NaOH and Na₂SiO₃ as the activators. However, the strength development and the work performance of were very low. Works need to be done to improve the performance to make use of alkali-activated recycled cement. In the present work, fully-hydrated cement pastes, as imitation of those hydrated cement pastes recycled from waste concretes, were prepared to prepare alkali-activated recycled cement, and the effect of slag powder as an active mineral admixture on strength development of alkali-activated recycled cement was studied, to find a way to improve the performance of alkali-activated recycled cement.

2. Experimental
2.1. Materials
Chinese P·II 42.5(OPC), P·S 42.5 and P·F 42.5 cements were used for preparing fully-hydrated hardened cement pastes for imitation of recycled cements pastes. S90 slag powder conforming to Chinese standards were used as active mineral admixture. Water glass with the SiO₂/Na₂O modulus of 1.4 was used as the activator.
2.2 Procedure

2.2.1 Preparing imitated recycled cements pastes
Cement pastes with water-to-cement ratio (w/c) of 1.0 were prepared with the P·II 42.5, P·S 42.5 and P·F 42.5 cements, steam cured at 99°C for 30 days, crushed and dried at 200°C for 2 h, and ground to powders with the specific area about 380 m² kg⁻¹. The powders, denoted as PII, PS and PF, respectively, were taken as the imitations of recycled cement paste from concrete with different original types of cements P·II 42.5, P·S 42.5 and P·F 42.5. The hydration degrees of the cement pastes as analyzed by Combined-Water Method are all higher than 95%.

2.2.2 Preparing and testing
Alkali-activated recycled cement pastes (AARCP) were prepared with the PII, PS and PF powders, and the mixtures of the powders added with 15% and 30% slag powder with the water-to-solid ratio (w/s) of 0.5. Water glass was added as the activator, with the addition of equivalent Na₂O 5% of the sum of therecycled cement paste and the slag powder. The pastes were denoted as, for example, PS and PIIS15, meaning that they were prepared from PS and from PII replaced by 15% slag powder, respectively. The pastes were formed to specimens of 20×20×80 mm and cured in a curing chamber of (20±1)°C and RH>90% for different ages. Mechanical strengths were tested at the age of 3, 28 and 90 day.

2.2.3 Microstructure characterization
The microstructures of the AARCP at 28 day were analyzed using an SU8010 Semi-In-Lens FE scanning electron microscope (SEM).

3. Results and Discussion

3.1. Effect of the Original Cement
Figure 1 shows strength of the recycled cement pastes prepared from PII, PF and PS. All the three pastes prepared from PII, PF and PS showed lower strengths. The highest compressive strength was only 22.5 MPa at 28 d, and 24.3 MPa at 90 d. The alkali activated PF has the highest strengths.

The cementing strength of the alkali-activated recycled cement has three contributors, the reconstruction of the hydrates of the cement paste under the reaction of alkali, the hydration of the unhydrated cement clinker in the cement paste, and the activation of unreacted active mineral admixture(s) such as slag and fly ash in the cement paste by alkali. Since the cement pastes of PII, PF and PS have subjected long ages of hydration, there are very few unhydrated cement clinker remained, the main differences between PII, PF and PS are the type and contents of the unreacted active mineral admixtures, slag and fly ash. PII contains no unreacted slag or fly ash, so that the alkali activated PII cement paste has the lowest strengths at each age. The glass phases in fly ash is basically less active than slag, there are more unreacted active particles remained in PF than PS, so that the alkali activated PF cement paste shows the highest strengths at each age.
3.2. Effect of Slag Replacement

When PII, PF and PS were partly replaced by slag, the strengths of the alkali activated recycled cement were greatly increased. Figure 2 shows the strengths of the recycled cement pastes prepared from PII, PF and PS, replaced by 0, 15% and 30% slag, respectively. The compressive strength and flexural strength of recycled cement pastes increase with the increasing of the replacement rate of slag powder. The flexural strengths increased by about 50%~400%, and the compressive strengths increased by about 30%~100%, according to the type of the recycled cement paste powder, the replacement of slag powder, and the age. Especially, the flexural strengths of PF with the slag powder replacement of 30% at 3, 28, and 90 d reached 3.8 MPa, 5.6 MPa and 6.7 MPa, and the compressive strengths reached 18.1 MPa, 41.0 MPa and 51.9 MPa, respectively.

Replacing the recycled cement powder partly by slag powder can not only increase the “unreacted glass particles” in the cement, which reacts with alkali and generates more newly formed hydrates and denser microstructure, but also increase the reconstruction of the original hydrates to regenerate cementitious property. According to the results, it is beneficial to replace recycled cement powder by 30% slag powder to prepare alkali-activated recycled cement which can be practically used.
3.3. Microstructures of Hardened Cement Pastes

Figure 3 shows the SEM photos of the hardened PF pastes without replacement (Figure 3a) and with 30% slag powder replacement (Figure 3b), respectively, cured for 28 days. The hardened PF pastes without replacement is composed mainly of granular particles probably of cement hydrates of the original cement paste, and quartz and mullite of the original, covered with newly formed gel-like hydrates, which are easy to be distinguished from the original ones by their different shapes. These gel-like hydrates, are presumably C–S–H, C–A–S–H and (N,C)–A–S–H gels [10–12]. These substances are hard to be distinguished from each other for their small sizes, disordered structures, variable compositions and close aggregation. There are larger volumes of pores between the particles. The loser structure is responsible for the lower strengths.

The hardened PF pastes with 30% slag powder replacement (PFS30) expressed totally different microstructure: the newly formed products enclosing the original ones and densely aggregated. The microstructure is very similar to those of alkali activated slag cement, which usually yields very high strength. There are no CH crystals detected. Under the attack of alkali, the slag powder as the replacement reacts with OH and the other components in the recycled cement to form C-S-H and (N,C)-A-S-H gels, which induces the break of the original C-S-H gel, part of the C-S-H gels and C-A-H gels were dissolved into the aqueous phase. On the other hand, [SiO₄]⁴⁻ offered from water glass and active mineral additives would be incorporated with the Na⁺, Ca²⁺ and Al³⁺ ions released from the cement paste to form C-S-H gels and C-A-H gels. Aqueous Ca modifies N-A-S-H gels with high levels of Na⁺ and Al³⁺, and then superseded part of sodium to form (N,C)-A-S-H gels. The densely aggregated microstructure explains the high strengths of the paste.

![SEM photos of hardened recycled cement paste](image)

**Figure 3.** SEM photos of hardened recycled cement paste

4. Conclusion

The strength of alkali-activated recycled cement paste depends on the types of the original cement. The alkali-activated recycled cement pastes prepared from the recycled cement pastes with the original cement of fly ash cement (PF) can results the highest strength, followed by that from slag cement, and the that from the ordinary Portland cement can results the lowest strength. Replacing recycled cement pastes partly by slag powder can greatly increase the strength of the alkali-activated recycled cement paste. Alkali-activated recycled cement paste with applicable strengths can be prepared by replacing 30% recycled cement powder with slag powder. Flexural and compressive strengths at 90 day as high as 6.7 MPa and 51.9 MPa, respectively, can be achieved. Replacing recycled cement powder with slag powder greatly results very dense microstructure, with is responsible for the higher strengths.

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