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1 **Role of recycled fine aggregates in regulating hydration behavior and** 2 **mechanical performance of alkali-activated slag mortars**

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11 **Abstract**

12 Recycled fine aggregates (RFA) contain old cement paste with relatively high alkalinity, which may
13 provide additional activation in alkali activated slag systems. In this study, RFA was used to replace river
14 sand at replacement ratios of 0%, 50% and 100% in alkali activated slag mortars. Liquid and solid sodium
15 silicate with Na₂O concentrations of 0%, 3%, 6% and 9% were investigated. The setting time, flowability,
16 compressive and flexural strengths, heat evolution and microstructure were evaluated. The results
17 showed that increasing the RFA content shortened the setting time but reduced the flowability of the
18 mortars. RFA also promoted strength development, particularly at early ages and moderate alkali
19 activator dosages. For mortars activated with 6% liquid sodium silicate, the 28-day compressive strength
20 increased from 50.9 MPa for 0% RFA to 57.2 MPa for 100% RFA. Even without an external alkali
21 activator, the mortar containing 100% RFA achieved a 28-day compressive strength of 13.7 MPa. The
22 main hydration peak of mortars containing 0%, 50% and 100% RFA appeared at approximately 81, 68
23 and 51 h, respectively, confirming the accelerating effect of RFA on slag hydration. SEM and EDS
24 observations further indicated that RFA promoted early-age microstructure densification, while the
25 attached old paste introduced a double-layer interface transition zone. Overall, the effect of RFA on alkali
26 activated slag mortar results from the competition between enhanced hydration and the adverse effects
27 associated with reduced flowability and interfacial defects.

28 **Key words:** Recycled fine aggregates; Mechanical properties; Alkali activator; Hydration behavior;
29 Interface transition zone

1. Introduction

With the rapid development of the global construction industry, the increasing demand for cement-based materials has resulted in substantial consumption of natural resources and significant carbon emissions. The production of ordinary Portland cement (OPC) is responsible for a considerable proportion of anthropogenic CO₂ emissions due to the energy-intensive calcination process and fossil fuel consumption. Therefore, reducing the environmental impact of cement production and developing low-carbon cementitious materials have become critical research objectives in the construction materials field [1–3]. Meanwhile, massive amounts of construction and demolition waste (CDW) are generated worldwide, creating challenges associated with landfill occupation and resource wastage. The development of sustainable building materials using industrial by-products and construction waste has therefore attracted increasing attention as an effective approach to achieving resource conservation and carbon reduction [4–6]. Among various alternatives, alkali-activated materials (AAMs) have been considered promising low-carbon binders because they can utilize industrial solid wastes as precursors and exhibit excellent mechanical properties and durability.

Ground granulated blast furnace slag (GGBFS), an industrial by-product from iron production, is widely used as a precursor for alkali-activated materials due to its latent hydraulic activity and high contents of CaO, SiO₂ and Al₂O₃. Compared with OPC-based binders, slag-based alkali-activated materials exhibit lower carbon emissions, reduced hydration heat, and improved resistance to chemical attack and permeability [7–9]. Under alkaline conditions, the glassy structure of GGBFS can dissolve and release reactive Si and Al species, which subsequently participate in the formation of C-(A)-S-H gels and contribute to strength development [10,11]. Previous studies have demonstrated that the type and dosage of alkali activators significantly influence dissolution behavior, hydration kinetics, and microstructural evolution of slag-based systems. Sodium silicate is one of the most widely used activators because it provides both hydroxyl ions and soluble silicate species, promoting the formation of compact reaction products [12,13]. However, practical applications of slag-based alkali-activated materials are still restricted by several issues, including rapid setting, excessive shrinkage, and the relatively high cost of alkaline activators [14,15]. Therefore, exploring alternative approaches to improve activation efficiency and reduce environmental impact remains necessary.

Recycled fine aggregates (RFA), obtained from crushed waste concrete, have attracted increasing

attention as sustainable substitutes for natural aggregates. Unlike natural sand, RFA generally contains attached old mortar, residual hydration products, and internal defects, resulting in higher porosity and more complicated surface characteristics. The incorporation of RFA into conventional concrete often leads to reduced workability, increased water demand, and deterioration of the interface transition zone (ITZ) due to the weak characteristics of attached old mortar [16–18]. However, recent studies have revealed that the attached old mortar in RFA is not completely inert. Residual cementitious phases, unhydrated particles, and Ca-rich components may participate in secondary reactions, while the alkaline environment provided by old mortar may contribute to the activation of reactive precursors [19,20]. Therefore, RFA has gradually been recognized as a potentially functional solid waste resource rather than merely a low-quality aggregate. Understanding the balance between its beneficial chemical contribution and adverse interfacial effects is essential for high-value utilization of RFA [21].

The combination of recycled aggregates and alkali-activated materials provides a promising strategy for synergistic utilization of construction waste. Previous studies have mainly focused on recycled coarse aggregates in alkali-activated slag concrete or geopolymer concrete. These studies demonstrated that recycled aggregates could be incorporated into alkali-activated systems while maintaining acceptable mechanical performance and durability characteristics [22–24]. In addition, the alkaline components and residual mortar attached to recycled aggregates were reported to influence hydration reactions and pore structure evolution [25]. However, existing studies mainly concentrate on recycled coarse aggregates, whereas the application of RFA in slag-based alkali-activated systems remains relatively limited. Compared with coarse aggregates, RFA possesses a higher specific surface area and larger amount of attached old mortar, which may generate more significant effects on slag dissolution, hydration kinetics, and ITZ evolution. Furthermore, the interaction mechanism between RFA-derived old mortar and slag activation, including the competition between accelerated hydration and interfacial defects, has not been fully clarified [26-29].

In this study, RFA was used to partially and completely replace natural river sand in alkali-activated slag mortars activated by liquid and solid sodium silicate. The effects of RFA replacement ratio and alkali activator dosage on the fresh properties, mechanical performance, hydration behavior, and microstructural characteristics of the mortars were systematically investigated. Setting time, flowability, compressive and flexural strength tests, isothermal calorimetry, and SEM-EDS analyses were conducted to reveal the contribution of RFA-derived old mortar to slag activation and the corresponding interfacial

effects. The findings provide new insights into the role of RFA in slag-based alkali-activated materials and promote the high-value utilization of construction and demolition waste in low-carbon cementitious systems.

2. Experimental Program

2.1 Materials

GGBFS produced in China Hebei with the density of 2.94 g/cm³ and blaine of 6786 cm²/g was used as raw material. The basicity coefficient (CaO+MgO/Al₂O₃+SiO₂) and the quality coefficient (CaO+MgO+Al₂O₃/SiO₂+TiO₂) according to the chemical composition are 1.27 and 2.27, respectively. The particle size distribution of GGBFS analysed by a Laser Particle Size Analyzer is given in Fig.1. The chemical composition of GGBFS are illustrated in Table 1.

Table 1. Chemical composition of GGBFS (wt.%)

Chemical composition	CaO	SiO ₂	Al ₂ O ₃	MgO	SO ₃	TiO ₂	Na ₂ O	Fe ₂ O ₃	Cl ⁻
Wt(%)	42.96	27.60	13.51	9.31	3.09	1.38	0.46	0.54	0.13

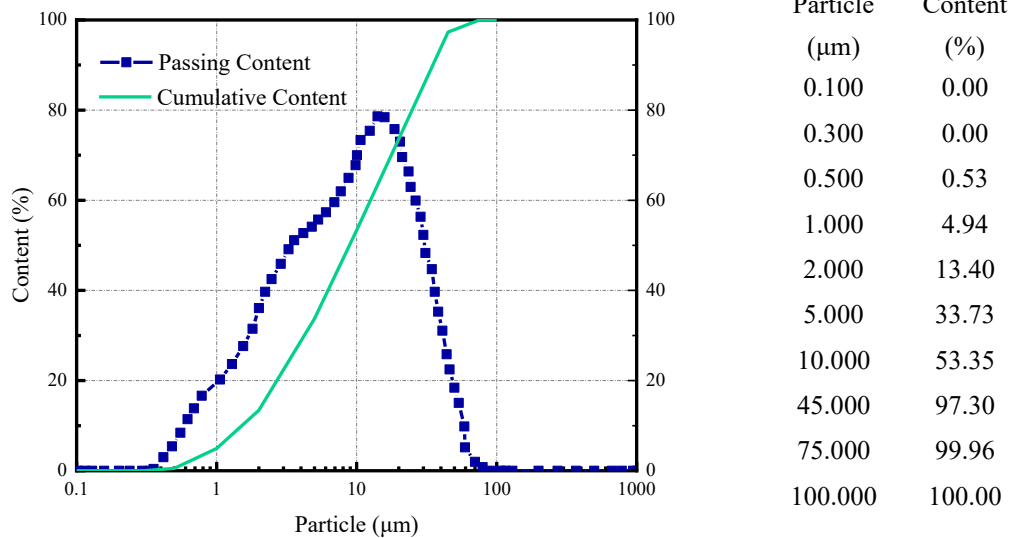


Figure 1. Particle size distribution of GGBFS

Two types of alkali activators including liquid sodium silicate and solid sodium silicate were used in this study. Solid sodium silicate powder with the purity of 99% which provided by a factory in China Shandong was used, the modulus (Ms, SiO₂/Na₂O) is 1. For liquid sodium silicate, sodium hydrate was added in the commercial water glass solution to adjusting the Ms of the solution as 1. The commercial water glass provided by China Hebei with 27.06 wt.% SiO₂, 8.57 wt.% Na₂O was used. The solid sodium

hydrate used to adjusting the Ms is provided by a factory in China Tianjin, with the purity of 99%.

River sand (RS) and crushed RFA are used as the fine aggregates in mortar. The river sand is obtained in China Harbin. The recycled fine aggregates (RFA) were obtained from recently demolished construction in China Harbin. After crushed by the jaw crusher, recycled fine aggregates are separated by the variation of particle ranges. The particle distribution of river sand is shown in Table 2. To reduce the variation, each particle size range of the recycled fine aggregates used in this study were adjusted to the same as the river sand. The physical properties and pH level of these two types of fine aggregates are illustrated in Table 3. To confirm the reason of different properties obtained by utilizing different aggregates, the chemical compositions of recycled fine aggregates and river sand are analysed by XRD, and provided in Table 4.

Table 2. Particle size distribution of river sand and recycled fine aggregates

Particle size (mm)	2.36-4.75	1.18-2.36	0.60-1.18	0.30-0.60	0.15-0.30	<0.15
Quality (%)	11.00	18.60	19.20	41.00	8.00	2.20

Table 3. Physical properties and pH level of river sand and recycled fine aggregates

	Density(cm ³ /g)	F.M.	Water absorption ratio (%)	pH
RS	2.88	2.87	10.83	7.8
RFA	2.38	2.87	2.11	11.3

Table 4. Chemical compositions of river sand and recycled fine aggregates (wt.%)

	SiO ₂	CaO	Al ₂ O ₃	Na ₂ O	K ₂ O	MgO	Cl ⁻
RS	75.59	1.39	13.18	3.28	4.42	0.11	0.02
RFA	60.40	16.96	10.65	1.87	3.10	1.00	0.13

2.2 Mortar mixes

In this study, the water to binder ratio (W/B) and binder to sand ratio (B/S) were fixed as 0.5 and 1:3, respectively. The sodium oxide concentration of alkali activators were 0 (plain), 3%, 6% and 9% by the total mass of GGBFS. The replacement ratios of recycled fine aggregates to river sand are 0, 50% and 100% for mass, respectively. Water in the liquid of sodium silicate and free water were both take into the consideration to identify the total mass of water to binder ratio is 0.5.

For the mixing of activators. When using liquid sodium silicate, solution is made by mixing commercial water glass, sodium hydroxide and free water to identify the Ms of the sodium silicate is 1, the volume of the water in the solution should be removed from the total free water. For the solid sodium silicate, it is previously dry blended with GGBFS for 30 seconds, and then adding the fine aggregates and water with 90 seconds mixing.

2.3 Experimental method

The setting time of the mortars were measured by Vicat apparatus in accordance with standard of JGJ/T 70-2009. Flowability of the mortars were tested by using flow table according to standard of GB/T 2419-2005.

The flexural and compressive strengths with the age of 1, 3, 7 and 28 days also are according to JGJ/T 70-2009. The size of the specimens are 40×40×160 mm. Mortars are cured in the curing box with the temperature of 20±2 °C and the relative humidity of 50%.

Scanning electron microscope investigations were done by a Zeiss Ultra Plus SEM. 1-2 mm thick small slices were obtained from the mortars, absolute ethyl alcohol was used to stop the hydration of the cementitious, then with a conductive coating.

Three samples of mortars with B:S of 1:1 and liquid sodium silicate of 3% were prepared to exam the hydration effect of RFA. The replacement ratio of RFA to natural fine aggregates are 0, 50 and 100%, respectively. Heat flow of mortars with 3% of liquid sodium silicate were analysed by TAM AIR calorimeter, the rate of heat liberation was tested for 4 days.



Figure 2. TAM Air Microcalorimeter



Figure 3 Field emission scanning electron microscope

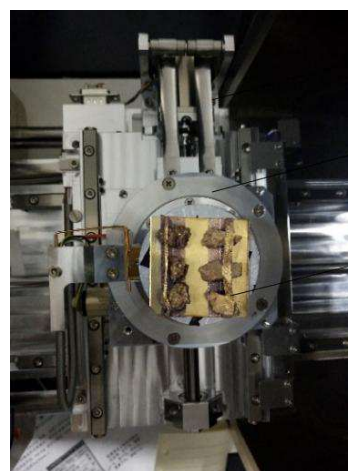


Figure 4 Microscopic sample

3. Experimental results

3.1 Setting time

The setting time of the mortars with the variation of alkali activators and sodium concentrations are shown in Fig. 5. It could be observed the setting times decreased with the increase of the dosages of alkali activators. Mortars with liquid sodium silicate generally hardened quicker than solid sodium silicate. These results are in agreement with studies by other researchers(). When the dosage of alkali activator is 0, mortar utilizing 100% of RS can not be hardened. However, 0% alkali activator mortars could be setting when 50% and 100% of RFA used as fine aggregates. It could be explained the latent hydraulic of GGBFS is activated by the alkaline composition of the RFA. Setting time reduced with the increase replacement ratio of RFA. The reason may also due to the high alkaline level of RFA. As known, setting time should be in the available range. The setting time for the mortar with 6% and 9% alkali activator shows very short setting time. Utilization of RFA could make the setting time even shorter. It seems mortar with RFA should be used in special concrete which need quick setting. Further study about utilization of recycled fine aggregates based alkali activated mortar on repairing materials or shotcrete are needed.

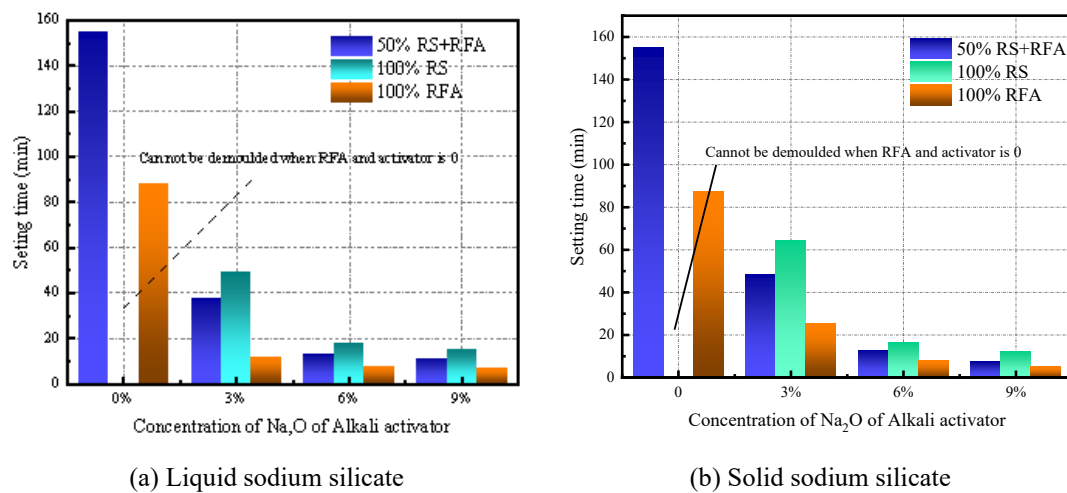


Figure 5. Setting time with various types and dosages of alkali activators

3.2 Flow tests

The flow values of the mortars are shown in Fig.6. For all the mixes, flow value obviously decreased with the increase replacement ratio of RFA. It is mainly due to the high water absorption of RFA attached high volume of free water. When the dosages of the replacement ratios of RFA are 0% and 50%, utilization of liquid sodium silicates show higher or similar flowability. These results are similar with many researchers. However, when the replacement ratios of the RFA are 100%, mixes utilizing liquid

sodium silicates generally show lower flowability than using solid sodium silicates. It may contribute to the spherical solid sodium silicate powder improve the structure in dry condition.

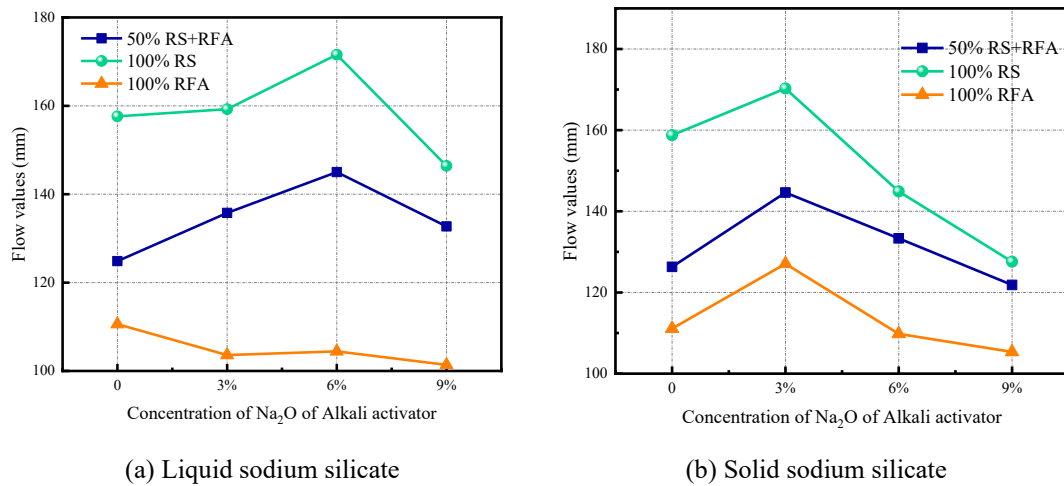


Figure 6. Flow values of the test mixes

3.3 Compressive strength

The results of compressive strengths are illustrated in Table 5. The compressive strengths of mortars with age are presented in Fig. 7.

When the concentration of alkali activator is 0, mortars with RS could not be demould until 7 days, the compressive strength is considered as 0. It is due to the lack of alkaline composition in the mortars, the hydration reaction is hardly to be continued. However, mortars with the RFA replacement ratio of 50% and 100% could obtain 10.20 and 13.70 MPa at 28 days, respectively. Compressive strength obviously increased with the increase replacement ratio of RFA. It can be explained by the alkali activation between GGBFS and the alkaline compositions in RFA. The pH level and CaO contents of RFA is higher than RS, latent hydraulic of GGBFS is activated.

With the increase of the alkali activator dosages, compressive strength increased. Using liquid sodium silicate generally obtained higher compressive strength than solid sodium silicate, the results are similar with many studies(). With the increase of alkali activator dosages, the extent of increase of liquid sodium silicate based mortars is larger than solid sodium silicate based mortars.

When the dosages of liquid sodium silicate are 3% and 6%, compressive strengths increased with the increase replacement ratio of RFA. When the replacement ratio of liquid sodium silicate is 9%, mortars with 100% of RFA show superior strengths before 7 days. However, in 28 days, mortars with 50% replacement ratio of RFA show most advanced compressive strength. It is due to the negative effects of the RFA influence the strength properties markedly than the positive effect via alkali activation.

When solid sodium silicate used as alkali activators, compressive strength increased with the increase replacement ratio of RFA at 1 day. However, for the 28 days compressive strengths, all the mortars with 100% of RS show superior results. It is considered as the insufficient reaction due to the low workability caused by the utilization of solid sodium silicate, defects of RFA show obvious effects.

Table 5. Compressive strength of mortars with age

Group	1 day		3 days		7 days		28 days	
	strength(MPa)		strength(MPa)		strength(MPa)		strength(MPa)	
	Liquid	Solid	Liquid	Solid	Liquid	Solid	Liquid	Solid
M-0-0※	0		0		0		0	
M-0-50	0		0		2.6		12.2	
M-0-100	0		4.5		10.1		13.7	
M-3-0	0	0	21.0	20.7	29.9	27.9	35.6	38.5
M-3-50	15.3	7.6	22.8	22.5	30.2	26.6	37.9	36.2
M-3-100	22.8	10.3	24.9	22.9	30.7	28.3	39.9	32.5
M-6-0	32.7	21.4	37.4	36.8	43.5	43.8	50.9	52.1
M-6-50	36.2	23.6	39.1	29.6	44.7	39.6	53.0	48.7
M-6-100	37.7	26.8	40.7	31.8	46.3	38.1	57.2	41.9
M-9-0	37.8	30.4	46.8	41.6	55.5	49.6	63.1	56.2
M-9-50	41.6	34.7	50.8	45.7	58.3	48.5	63.7	53.2
M-9-100	43.3	38.3	53.1	43.1	57.6	48.0	61.2	47.1

※For the mortars, the first number represents the concentration of alkali activator, the second number represents the replacement ratio of RFA. For example, M-0-0 means the sample with the dosage of alkali activator 0% and RFA 0%.

Table 6. Flexural strength of mortars with age

Group	1 day		3 days		7 days		28 days	
	strength(MPa)		strength(MPa)		strength(MPa)		strength(MPa)	
	Liquid	Solid	Liquid	Solid	Liquid	Solid	Liquid	Solid
M-0-0※	0		0		0		0	
M-0-50	0		0		0.9		3.1	
M-0-100	0		1.5		3.9		4.7	
M-3-0	0	0	4.4	4.7	5.6	6.0	6.6	6.3
M-3-50	1.7	2.2	5.0	5.4	6.0	6.2	6.7	7.2
M-3-100	3.4	2.6	6.1	5.7	7.6	6.2	7.8	7.3
M-6-0	4.0	3.7	7.0	6.6	7.3	7.6	7.9	7.0
M-6-50	4.3	4.2	8.1	6.0	8.4	6.8	7.2	7.1
M-6-100	6.0	4.4	8.3	7.3	9.0	7.9	8.1	7.6
M-9-0	5.0	4.2	6.9	7.0	7.1	7.1	7.0	6.9
M-9-50	5.4	5.6	8.4	8.2	8.5	8.3	7.9	7.4
M-9-100	6.3	6.1	8.6	8.4	8.9	8.8	7.7	7.1

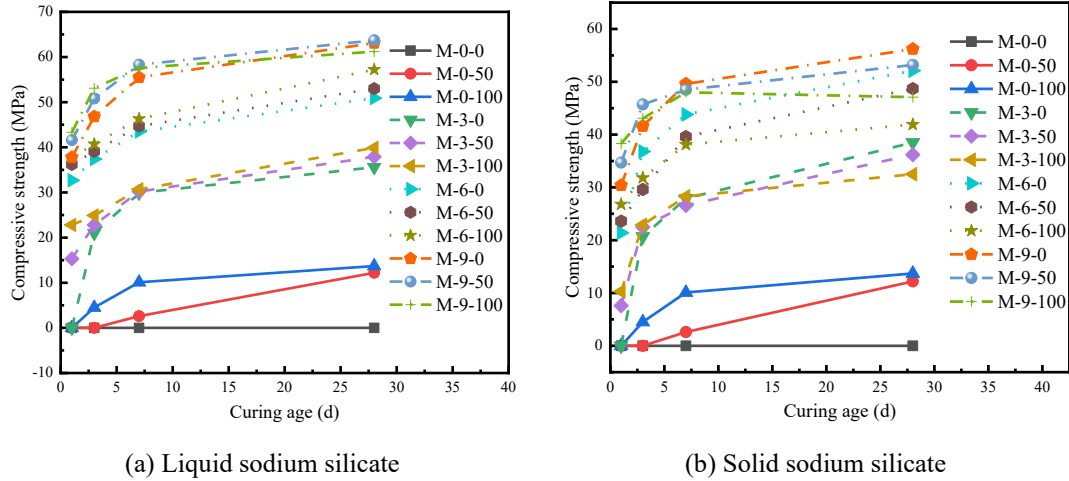


Figure 7. Compressive strength of alkali activated mortar

3.4 Flexural strength

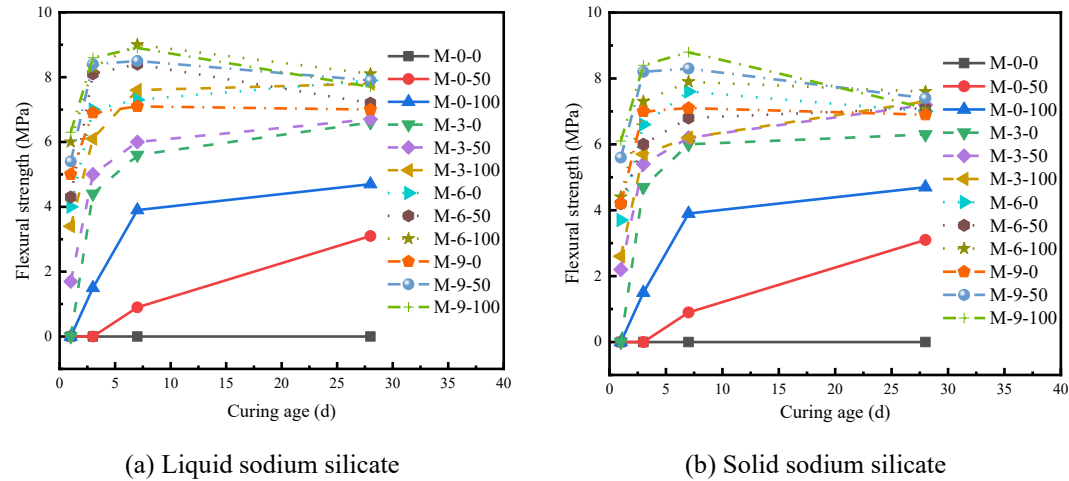


Figure 8. Flexural strength of alkali activated mortar

The flexural strength values of the mortars are provided in Table 6. The flexural strength with age are shown in Fig. 8.

Generally, flexural strength increased with the increase of sodium concentration. Mortars with liquid sodium silicate show higher flexural strength than solid sodium silicate. The reasons are similar with compressive strength. With the increase of sodium concentration, the increase range of flexural strength is smaller than compressive strength.

However, strength with high concentration of sodium decreased in 28 days. Mortars with solid sodium silicate shows more serious strength retraction problem than liquid sodium silicate. It may due to the cracks in high concentration sodium mortars.

3.5 Heat of hydration

The heat evolution curves of mortars with different replacement ratio of RFA are shown in Fig. 9. There are generally 2 peaks for each sample. The first peak of each sample appears very rapidly. This

peak may generally attribute to the initial reaction between GGBFS and liquid sodium silicate. With the increase replacement ratio of RFA, the peak value also increased. It may due to the high volume of CaO participated in the hydration process. The second peak of each sample may attribute to the main hydration reaction, C-S-H gel may formed in this period. The sample with 0% of RFA shows the peak at 81 hours, whereas samples with 50% and 100% of RFA show the peak at 68 and 51 hours, respectively. Addition of RFA advanced the peak. It is generally due to the quality coefficient of mortar increase with the increase usage of RFA. High volume of CaO also increase the pH level and supplement the alkaline level of the mortar, the hydration reaction became quicker. The beginning of the second hydration period of sample with 50% RFA is only 10 hours later than 100% RFA sample, and ended 13 hours earlier than 0% RFA sample. The slope of sample with 50% RFA is flatter, and the peak value of 50% RFA is lower than the other samples. The average heat value of 0% and 100% RFA samples at different time show very small difference with 50% RFA sample.

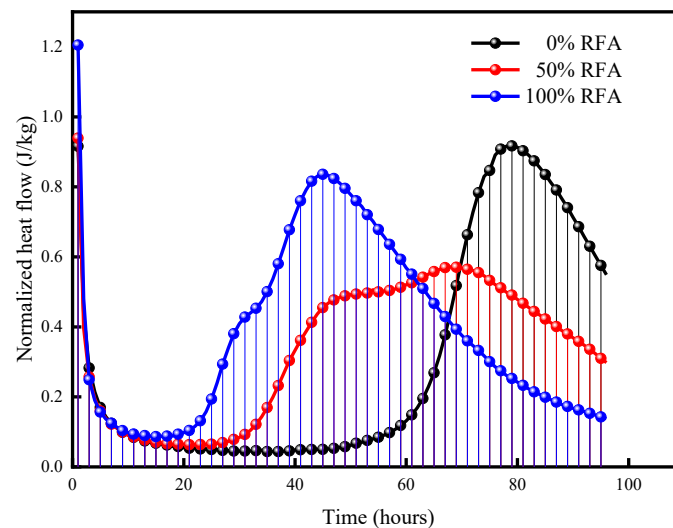


Figure 9. Heat evolution curves of mortars with various replacement ratio of RFA

3.6 SEM analysis

Double layers interface transition zone (ITZ) existed in concrete when recycled aggregates used. ITZ may lead to the defects in concrete. SEM images of mortars with 100% of RFA and 3% liquid sodium silicate were observed at 3 and 28 days, ITZ of the samples are focused. The EDS analysis of spots 1 and 2 are shown in Fig. 11.

It can be observed mortars at 3 and 28 days are both with 2 layers of ITZ. The first layer of ITZ is between sand and old paste attached in the surface of RFA. The second layer of ITZ is between old paste and new paste.

Compared with mortars with curing age of 3 days, the gap between sand and old attached paste became thicker. This phenomenon could explain the negative effect of ITZ increased with age developed. However, the thickness of attached old paste became slicer with age developed. The width of attached old paste with curing age of 3 days is twice the size of 28 days paste. According to the EDS results, the element concentrations of Na, Mg and Al significant declined.

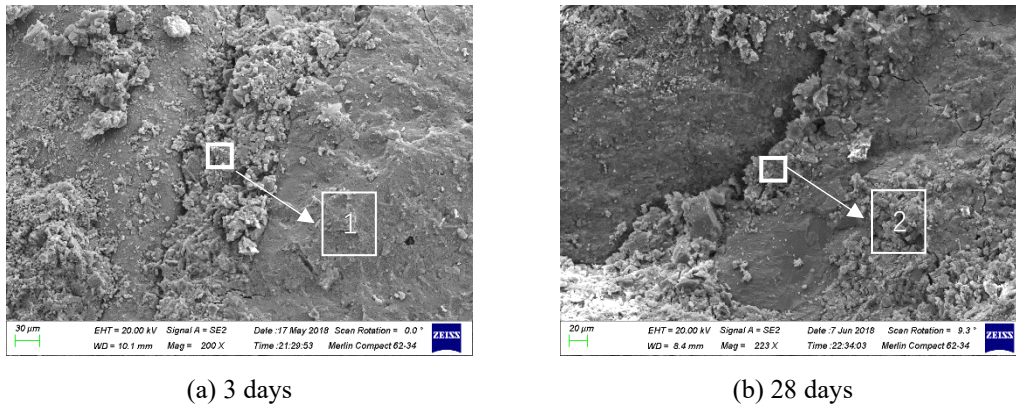


Figure 10. SEM imagines of ITZ zone of mortars with RFA

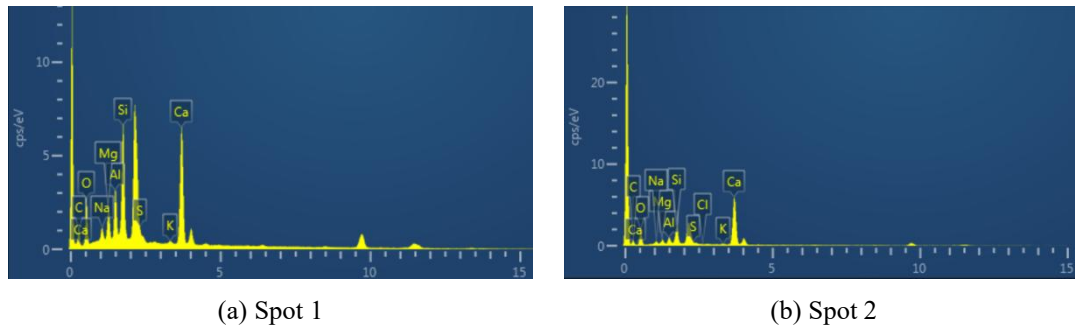
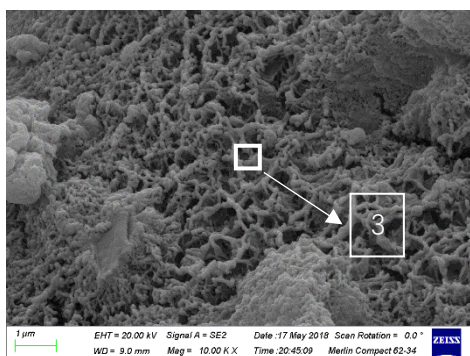
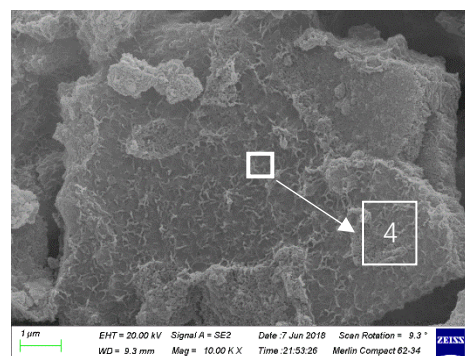


Figure 11. EDS analysis of ITZ zone of mortar with RFA

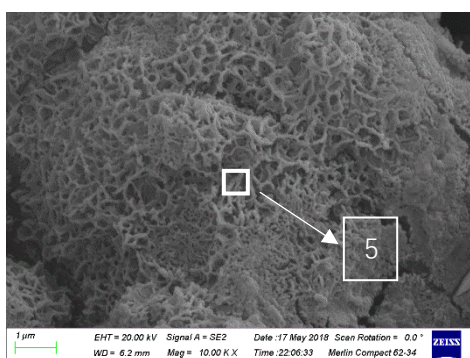
Fig. 12 shows the SEM images of mortars with various replacement ratio of RFA at 3 and 28 days. At 3 days, all the mortars show reticulation structure, with the increase replacement ratio of RFA, the structure became denser. At the age of 28 days, the reticulation substances change to plate-like. According to the EDS results, with the increase replacement ratio of the RFA, the element of Ca increased significantly. The quality coefficient of mortars also increased with increase of RFA at both 3 and 28 days. Thus, the strength of mortar increased with the application of RFA as mentioned before.



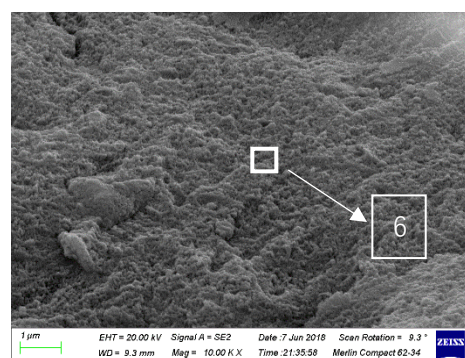
Mortars with 0% of RFA



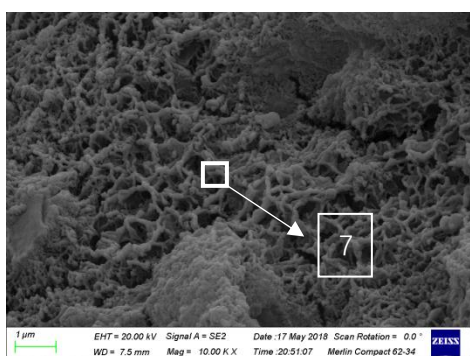
Mortars with 0% of RFA



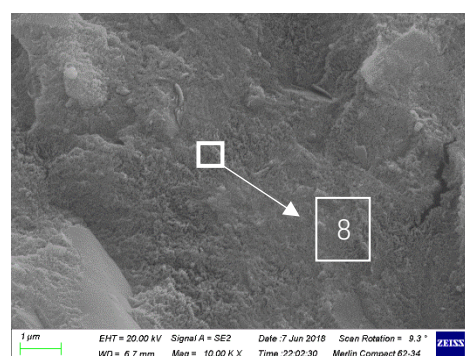
Mortars with 50% of RFA



Mortars with 50% of RFA



Mortars with 100% of RFA



Mortars with 100% of RFA

(a) 3 days

(b) 28 days

Figure 12. SEM images of mortars with various replacement ratio of RFA at age

Fig. 13 shows the EDS analysis of spots 3 to 8 from different samples. With the increase replacement ratio of RFA, the element of Ca in hydration products increased significantly, this part of Ca is obtained from old paste in RFA. The decreased volume of old paste adhered to the surface of RFA attend hydration and shows positive effects on active the latent hydraulic of GGBFS.

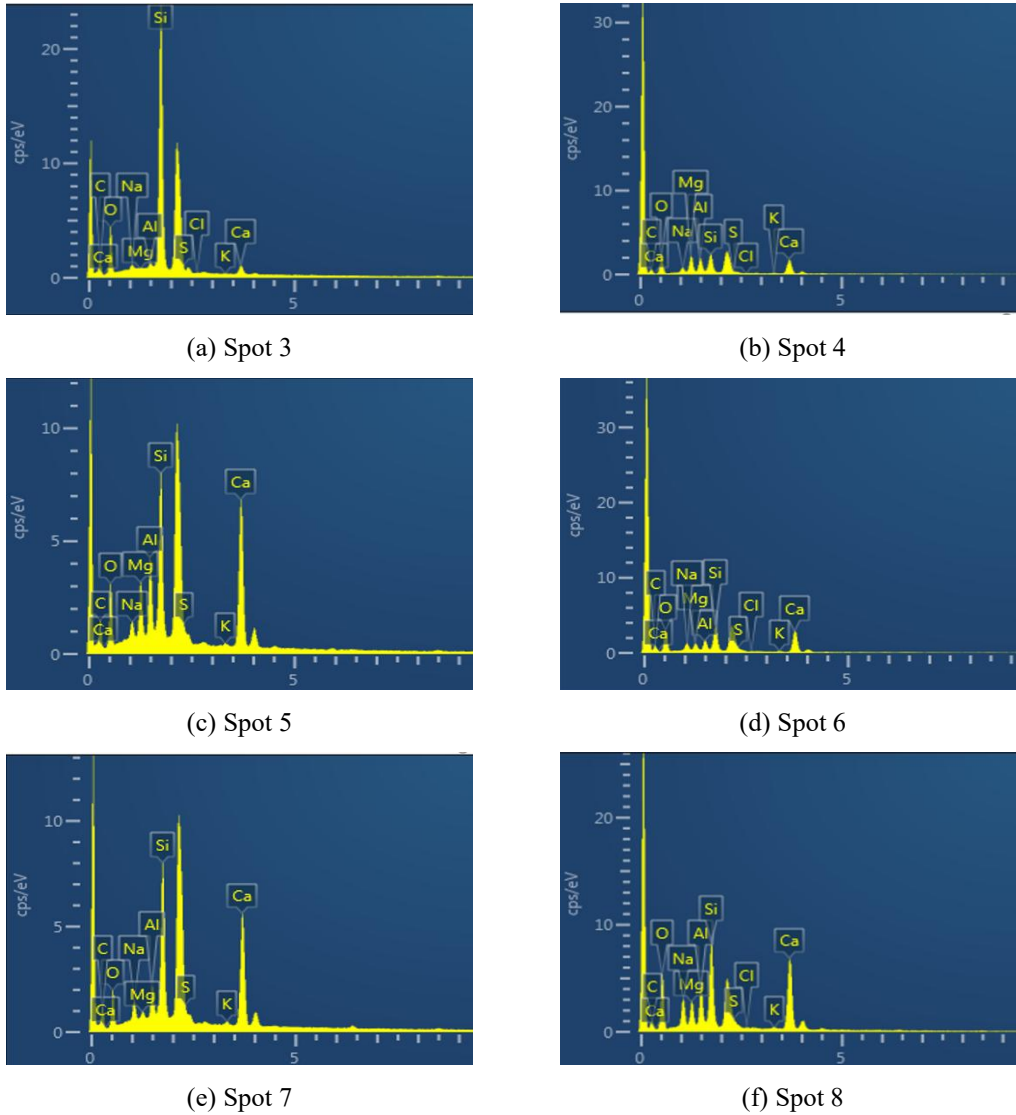


Figure 13. EDS analysis of samples with various of RFA and age

4. Discussions

Based on the macroscopic and microstructural results, RFA plays a dual role in alkali activated slag mortar. The old paste attached to RFA contains alkaline and Ca-rich components, which can promote the activation and hydration of GGBFS. This effect is supported by the shorter setting time and the earlier hydration peak with increasing RFA content. For mortars with 3% liquid sodium silicate, the main hydration peak shifted from approximately 81 h for 0% RFA to 68 and 51 h for 50% and 100% RFA, respectively. SEM and EDS results also showed a denser microstructure and increased Ca content with increasing RFA replacement ratio, which is consistent with the improved early-age strength.

However, RFA also introduces adverse effects. The attached old paste forms two layers of interface transition zone (ITZ), including the interfaces between the original sand and old paste and between the

old paste and new paste. Meanwhile, the reduced flowability caused by RFA may increase local defects in the mortar. Therefore, the strength development of RFA-based mortar is governed by the competition between the positive effect of accelerated hydration and the negative effects of reduced flowability and the double-layer ITZ. This explains why RFA is more beneficial to early-age strength, while its advantage becomes less pronounced at later ages or at high replacement ratios.

5. Conclusions

In this study, recycled fine aggregates (RFA) were used to replace river sand in alkali activated slag mortars activated by liquid or solid sodium silicate. Based on the fresh properties, mechanical performance, heat evolution and microstructural observations, the following conclusions can be drawn:

(1) The incorporation of RFA shortened the setting time and reduced the flowability of alkali activated slag mortar. Notably, mortars containing RFA could harden even without an external alkali activator, whereas the mortar containing only river sand could not be demoulded, indicating that the alkaline components in RFA contributed to the activation of GGBFS.

(2) The effect of RFA on mechanical properties depended strongly on the type and dosage of alkali activator. With 6% liquid sodium silicate, the 28-day compressive strength increased from 50.9 MPa for 0% RFA to 57.2 MPa for 100% RFA, corresponding to an increase of approximately 12.4%. However, at 9% activator dosage, the 28-day compressive strength reached 63.7 MPa at 50% RFA but decreased to 61.2 MPa at 100% RFA, showing that the beneficial effect of RFA became less pronounced at high alkali concentration and high replacement ratio.

(3) RFA significantly accelerated the hydration process. For mortars activated with 3% liquid sodium silicate, the main hydration peak shifted from approximately 81 h for 0% RFA to 68 and 51 h for 50% and 100% RFA, respectively. This acceleration is consistent with the higher alkalinity and Ca-rich components associated with the old paste attached to RFA.

(4) SEM and EDS observations showed that increasing RFA content promoted a denser microstructure at early ages and increased the Ca content of the hydration products. However, RFA also introduced a double-layer interface transition zone (ITZ) between the original sand, old paste and new paste. Therefore, the mechanical performance of RFA-based mortar is governed by the competition between accelerated hydration and microstructure densification on the one hand, and reduced flowability and interfacial defects on the other.

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Declarations

Clinical Trial Registration: Not applicable. This study is not a clinical trial.

Consent to Publish declaration: Not applicable.

Ethics and Consent to Participate declarations: Not applicable.

Data availability

The datasets generated during and/or analysed during the current study are not publicly available due to the requirement of keeping enterprise proprietary research and development achievements confidential, but are available from the corresponding author on reasonable request.

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