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Performance Comparison of Crumb Rubber in Ordinary Portland Cement and Alkali-Activated Slag: A Study on Pastes and Mortars

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ABSTRACT

The incorporation of crumb rubber (CR) as a partial replacement in cementitious materials offers a dual benefit of enhancing sustainability in construction and mitigating environmental issues associated with waste tire disposal. This research presents a comparative investigation of the mechanical performance of CR in Ordinary Portland Cement (OPC) and Alkali-Activated Slag (AAS)-based pastes and mortars. Experimental programs were conducted using CR as a partial replacement for binder materials (0%, 9.4%, 17.9%, and 25.5% by volume) and fine aggregates (0%, 9.4%, 17.9%, 25.5%, and 32.4% by volume). Compressive and flexural strengths were evaluated at curing ages of 7 and 28 days. The results indicate that compressive strength decreases progressively with increasing CR content due to weak interfacial bonding and the inherent elasticity of CR particles. However, AAS-based mixes exhibited better performance compared to OPC, particularly in terms of post-curing strength and resilience at moderate CR contents (9.4% -17.9%). This improved behavior is attributed to the dense microstructure and geopolymeric nature of AAS, which enhances CR- mixes interaction and reduces strength loss. Furthermore, the incorporation of CR contributed to improved ductility and altered failure modes, although excessive CR content led to increased porosity and reduced mechanical performance. Overall, the findings demonstrate that AAS mixes possess greater adaptability to CR incorporation than OPC mixes, highlighting their potential for sustainable construction applications.

INTRODUCTION

The increasing volume of end-of-life tires constitutes a major global environmental challenge, as they resist degradation and occupy significant space in landfills. A promising solution to this issue is the incorporation of CR, derived from waste tires, into cementitious binder materials. This approach offers a dual advantage: it enables the sustainable utilization of waste materials while simultaneously enhancing the performance of cementitious systems under specific conditions, as reported by Adak *et al.* (2017). OPC is widely used as the primary binder in concrete; however, its production generates significant carbon dioxide (CO_2) emissions. Previous studies have reported mixed results regarding the incorporation of CR into OPC-based mixes: CR incorporation generally reduces the compressive strength of cementitious mixes due to poor interfacial bonding and the low stiffness of rubber particles; however, as reported by Wang *et al.* (2018), that, it enhances ductility, energy absorption, and impact resistance. In general, increasing CR content leads to greater strength reduction, particularly when CR is used as a partial replacement for binder materials or fine aggregates.

Geopolymer binders, particularly AAS, have been identified as sustainable alternatives to OPC, as reported by Ahmad *et al.*(2023). AAS is produced by activating industrial by-products using alkaline solutions, typically including: industrial by-products such as ground granulated blast furnace slag (GGBS), which are activated using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Deventer *et al.* (2010), have reported that, these binder materials have been widely recognized for their superior mechanical properties, chemical durability, and environmental advantages. They also possess a dense microstructure and low calcium hydroxide content, which provide greater resistance to chemical attack, as well as reduced shrinkage and porosity, as reported by He *et al.* (2023).

Recent studies on CR-modified AAS composites have shown that these mixes may exhibit better performance than OPC mixes when CR is incorporated, as mentioned Barbhuiya *et al.* (2024). For instance, previous studies Zrar *et al.* (2022), have shown that the inclusion of CR in AAS matrices can enhance flexural strength and durability by improving matrix bonding and reducing porosity. Wang *et al.* (2022) also reported that the incorporation of CR in AAS mixes maintains workability and enhances resistance to cracking. Aslani *et al.* (2019) emphasized the need for direct comparison between AAS and OPC binder mixes incorporating CR, particularly in paste and mortar forms. Most previous studies have focused on full concrete systems or a single binder type, whereas comparative investigations of fundamental material behaviour (e.g., early-age strength and flexural performance) remain limited, as reported by Guo *et al.* (2022). Since paste and mortar properties significantly influence overall concrete

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performance, particularly in hydraulic, precast, and architectural applications, this knowledge gap is critical.

There has been a recent increase in research on the incorporation of CR in AAS-based systems. Initial studies suggest that CR exhibits higher compatibility with AAS matrices than with OPC mixes due to differences in pore structure, alkalinity, and chemical interactions. Additionally, previous studies by Xie *et al.* (2019) have shown that AAS-based rubberized mixes exhibit improved crack resistance and post-peak ductility, which are critical for impact-resistant and energy-dissipating applications. Furthermore, Xie *et al.* (2019) demonstrated that composites incorporating AAS and CR exhibit superior flexural performance and enhanced resistance to environmental degradation compared to those based on OPC. The denser matrix and reduced free lime content in AAS compared to other binders may promote better encapsulation of CR particles and reduce the formation of weak interfacial transition zones (ITZs), which was attributed to such improvement in the properties of AAS, as mentioned by Waqas *et al.* (2021). Additionally, Luan *et al.* (2023) observed that AAS-based rubberized mixes exhibit better crack resistance and post-peak ductility, which are critical for impact-resistant and hydraulic wave energy dissipation applications. Nevertheless, the incorporation of CR in both binder mixes results in strength reductions, particularly at high CR contents (typically >17.9-25.5% by volume), due to the inherent flexibility and hydrophobic nature of CR, which weaken matrix bonding and promote void formation.

Although there is increasing interest in this field, current research has largely focused on either OPC or AAS mixes individually, and primarily on concrete rather than paste or mortar, as reported by Batayneh *et al.* (2008). A significant knowledge gap exists regarding the direct comparison of the mechanical behavior of OPC and AAS -based pastes and mortars containing CR. This is particularly important because paste and mortar properties including early-age strength development, bond strength, and fracture energy directly influence overall concrete performance, especially in repair mortars, precast elements, and thin overlays, as explained by Ding *et al.*(2018). Moreover, Khan *et al.* (2023) reported that, flexural performance has received limited attention in previous studies, despite its critical role in evaluating the ductility and cracking behavior of CR-modified composites. Although CR particles are known to act as stress redistributors in brittle matrices, their performance is highly dependent on particle size, surface roughness, replacement type (binder or aggregate), and matrix composition.

When binder cementitious partial replaced with CR in OPC-based mixes, this usually results in a more pronounced loss in strength stemming from the hindrance of formation of hydration products. Fine aggregates can be partially replaced by CR with marginally better performance, but the strength reduction still is quite substantial, as reported by Bengar *et al.* (2020). In AAS mixes, the surface oxidation of CR may be induced by the highly alkaline environment, which improves particle matrix bonding, although chemical degradation is still a concern in the long term, as reported by Ju *et al.* (2020). However, differences in the pore structure, shrinkage behaviour and matrix rigidity between OPC and AAS make it likely that a similar mix design will make different mechanical responses. This laboratory-based study investigates the behavior of pastes and mortars rather than concrete alone, providing deeper insight into CR binder interactions and their implications for mix optimization. Pastes isolate matrix behavior, while mortars provide insight into aggregate CR interactions; both are essential for composite design.

Therefore, this study provides a comprehensive experimental comparison of CR performance in OPC and AAS-based pastes and mortars. The objectives are to:

- To evaluate the compressive and flexural strengths of mixtures incorporating CR at 0-25.5% replacement of binder volume and 0-32.4% replacement of fine aggregate (FA) volume.
- To investigate the effect of CR replacement type (binder, fine aggregate, and combined replacement) on mechanical performance.
- To compare the mechanical responses of OPC and AAS -based mixes under identical testing conditions.

MATERIAL AND METHODS

Ordinary Portland cement Binder Materials

The primary binder used in OPC mixes was commercially available Ordinary Portland Cement (P.O. 42.5, CONCH brand), conforming to ASTM C150 (2009). The cement had a specific gravity of 3.15 and a bulk density of 3100 kg/m^3. Its chemical composition complied with the requirements for structural applications, as presented in Table 1.

Alkali-Activated Slag Binder Materials

The AAS binder was prepared using S95-grade slag powder as the precursor material. The geopolymerization reaction was initiated by activating the slag with a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The slag had a specific gravity of 2.9, a bulk density of 2.84 g/cm^3, and a Blaine surface area of 472 m^2/kg. Its chemical composition is characterized by high contents of CaO, SiO_2, and Al_2O_3, making it suitable for alkali activation, as shown in Table 1.

Table 1: Chemical compositions of OPC and slag (wt. %) (Liu *et al.,* 2025)

OPC 42.5 grade	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**Fe_2O_3**	**TiO_2**	**SO_3**	**Cl**	**others**
	60-65	20-22	5-6	≤ 5	3-4	-	≤ 3	≤ 0.1	-
S95-grade slag	37.25	34.11	15.32	8.49	0.73	1.94	-	-	2.16

Sodium Silicate Activator Solution

A sodium silicate (Na_2SiO_3) solution was used as the activator for all AAS mixes. The activator dosage was adjusted to achieve an activator-to-slag ratio of 5% by weight. Rihan *et al.* (2024) demonstrated that to ensure temperature stability and reaction equilibrium, the activator solutions were prepared 24 hours in advance.

Natural Fine Aggregates Filling Materials

Natural fine aggregates (FA), consisting of river sand, were used in this study. The sand had a bulk density of 1600 kg/m³, a specific gravity of 2.65, and a particle size range of 0.075-4.75 mm (passing sieve No. 4). The fineness modulus was 2.8, and the water absorption capacity was 2%, conforming to ASTM C33 (2003).

Crumb Rubber as Binder Materials

Crumb rubber (CR), used as a partial binder replacement, was purchased from a local factory in Nanjing, China. The particle size ranged from 300-600 μm (approximately passing 200 mesh).

Crumb Rubber as Fine Aggregates Materials

For partial replacement of fine aggregates, CR with a particle size range of 0.075- 4.75 mm and a specific gravity of 1.13 was used, conforming to ASTM D5603 (2003).

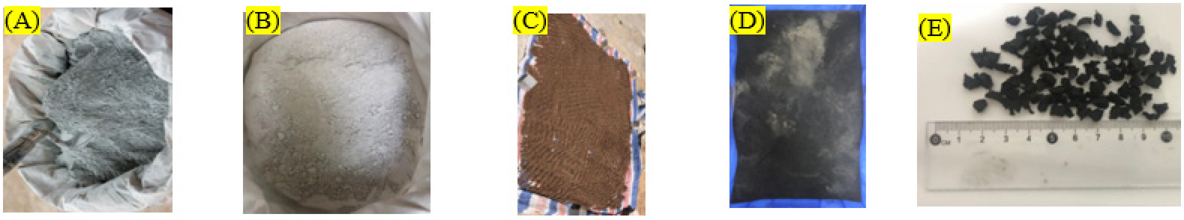


Figure 1: materials used in this study: (A) OPC binder; (B) SLAG binder; (C) Natural FA (Sand); (D) CR as binder materials and; (E) CR as FA

Water

Tap water was used for all mix preparations; it was free from harmful impurities such as acids and alkalis and suitable for both mixing and curing.

Specimen Preparation and Curing

In this study, OPC and AAS -based pastes and mortars were prepared with partial replacement of CR by volume percentage. CR was used as a partial replacement for both binder materials and fine aggregates (FA). The molds were cleaned, sealed at the base, and oiled prior to casting. The mixtures were placed into the molds in three layers. Total 24 different mix proportions were tested, resulting 144 specimens for flexural strength (size: 40 x 40 x 160 mm) and 288 specimens for compressive strength (size: 40 x 40 x 40 mm). The top surfaces of the specimens were immediately covered with plastic film after casting. After 24 hours, specimens were demolded and placed in a curing room at a constant temperature (20 ± 2°C, RH ≥ 95%) for 7 and 28 days for compressive and flexural strength testing, as shown in Figure 2.

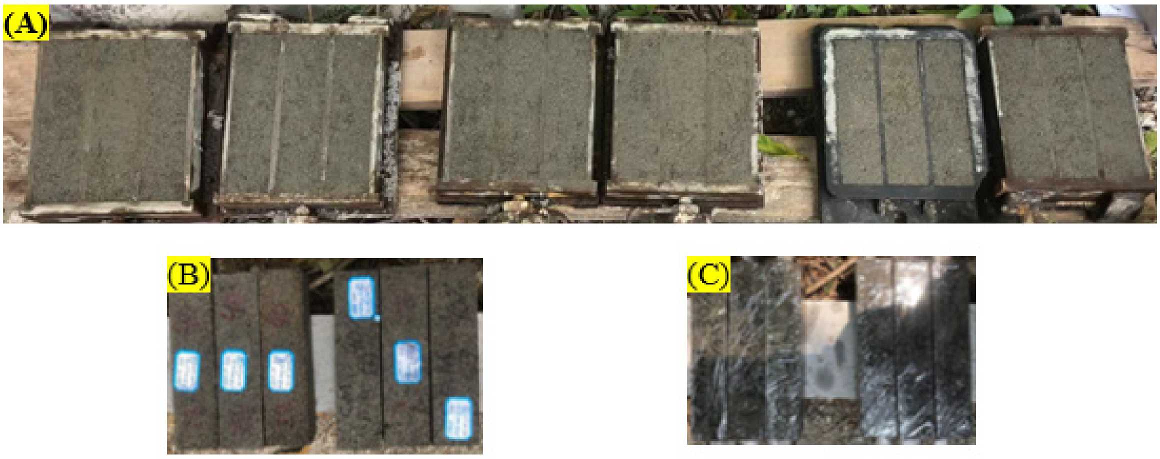


Figure 2: Experimental specimens (A) specimen casting (B) specimen labelling and; (C) specimen plaster covering.

Flexural Strength

Flexural strength tests were conducted in accordance with ASTM C348 (2008) using a centre-point loading method. The tests were performed using a universal testing machine (UTM) at a loading rate of 44 MPa/s on specimens measuring 40 × 40 × 160 mm. The specimens typically fractured into two parts upon reaching their maximum load. To minimize experimental error, the average value of three specimens was considered, as illustrated in Figure 3A and 3B.

Compressive Strength

Compressive strength tests were conducted in accordance with ASTM C349 (2013). Half of the specimens (40 × 40 × 160 mm) previously used in flexural testing were utilized for compressive strength evaluation. The compressive strength tests were performed using a universal testing machine (UTM) at a loading rate of 0.1-0.3 MPa/s, as illustrated in Figure 3C and 3D.

Figure 3: illustrates the failure modes of flexural and compressive strength specimens of OPC and AAS prisms incorporating CR as a partial replacement. Panel (A) shows the failure modes of OPC mortar prisms with 9.4 % CR as a binder partial replacement. Panel (B) depicts the failure modes of AAS mortar prisms with 32.4% CR as FA partial replacement. Panel (C) shows the failure modes of AAS mortar cubes with 9.4% CR as binder partial replacement, while Panel (D) displays the failure modes of OPC mortar cubes with 32.4% CR as FA partial replacement.

Experimental Design (Mix Proportions)

This study established a unified mix design for rubberized pastes and mortars to evaluate compressive and flexural strengths. For each mix, six specimens were cast (n=3,7d;n=3,28d). Both OPC and AAS based pastes and mortars were prepared and tested under identical conditions. All mixtures used a constant water-to-cement ratio of 0.40. OPC rubberized paste and mortar proportions followed ACI 211.1. For AAS rubberized pastes and mortars, alkali activation employed alkaline activator solutions with GGBFS as the binder. This design enabled systematic assessment of the effects of CR particle size and partial replacement level on mechanical properties.

Table 2: Mix Proportions and Experimental design of OPC and AAS based Pastes and Mortars.

Type of mix proportions	**Specimen Label**	**Mix. No. (CR in volume %)**	**OPC and AAS (kg)**	**Fine aggregates (kg)**	**CR (kg)**	**Flexural Strength Test**	**Compressive Strength Test**
OPC paste/ OPC replacement	C0	0	1.00	-	0.00	7d,28d	7d,28d
	C10	9.4	0.96	-	0.04	7d,28d	7d,28d
	C20	17.9	0.93	-	0.07	7d,28d	7d,28d
	C30	25.5	0.89	-	0.11	7d,28d	7d,28d
OPC mortar /OPC replacement	C-C0	0	0.24	0.76	0.00	7d,28d	7d,28d
	C-C10	9.4	0.23	0.76	0.01	7d,28d	7d,28d
	C-C20	17.9	0.22	0.76	0.02	7d,28d	7d,28d
	C-C30	25.5	0.22	0.76	0.03	7d,28d	7d,28d
OPC mortar /Fine aggregates replacement	C-FA10	9.4	0.24	0.73	0.03	7d,28d	7d,28d
	C-FA20	17.9	0.24	0.69	0.06	7d,28d	7d,28d
	C-FA30	25.5	0.24	0.66	0.10	7d,28d	7d,28d
	C-FA40	32.4	0.24	0.63	0.13	7d,28d	7d,28d
AAS paste/ slag replacement	S0	0	1.00	-	0.00	7d,28d	7d,28d
	S10	9.4	0.96	-	0.04	7d,28d	7d,28d
	S20	17.9	0.92	-	0.08	7d,28d	7d,28d
	S30	25.5	0.88	-	0.12	7d,28d	7d,28d
AAS mortar /slag replacement	S-S0	9.4	0.25	0.75	0-.00	7d,28d	7d,28d
	S-S10	17.9	0.24	0.75	0.01	7d,28d	7d,28d
	S-S20	25.5	0.23	0.75	0.02	7d,28d	7d,28d
	S-S30	32.4	0.22	0.75	0.03	7d,28d	7d,28d

AAS mortar / Fine aggregates replacement	S-FA10	9.4	0.25	0.72	0.03	7d,28d	7d,28d
	S-FA20	17.9	0.25	0.69	0.06	7d,28d	7d,28d
	S-FA30	25.5	0.25	0.66	0.10	7d,28d	7d,28d
	S-FA40	32.4	0.25	0.62	0.13	7d,28d	7d,28d

RESULTS AND DISCUSSION

Results

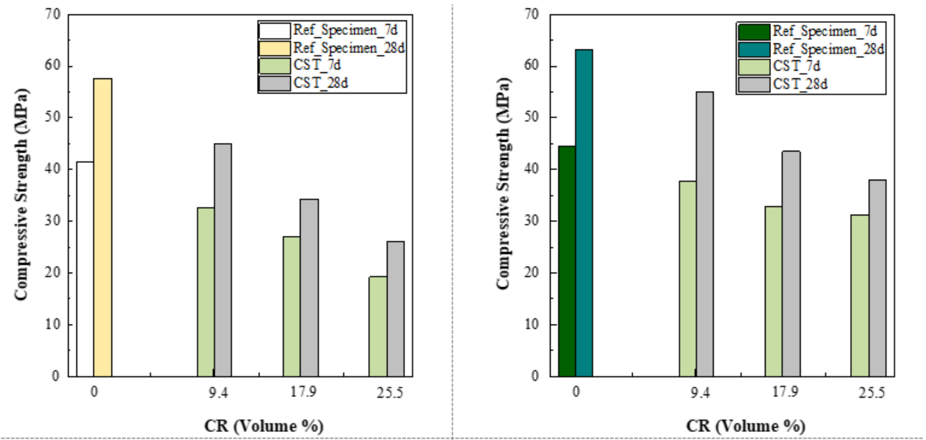
The effects of CR content and particle size on compressive and flexural strength were evaluated in accordance with relevant ASTM standards. Tests were conducted on both OPC and AAS pastes and mortars. For each mixture, three specimens were tested at each curing age, and the reported values represent the arithmetic mean (n = 3) to minimize experimental error.

Compressive Strength of OPC and AAS Pastes with CR Partial Binder Replacement at 7 and 28 Days

For OPC paste with CR as a partial binder replacement, the control sample (0% CR) achieved strengths of 41.5 MPa and 57.6 MPa at 7 and 28 days, respectively. At CR contents of 9.4%, 17.9%, and 25.5%, the 7-day strengths decreased to 36.6, 27.0, and 19.3 MPa, corresponding to reductions of 11.8%, 34.9%, and 53.5%, respectively, compared to the control. At 28 days, the strengths were 45.0, 34.3, and 26.0 MPa, representing reductions of 21.9%, 40.3%, and 54.9%, respectively (Figure 4A). For AAS paste with CR as a partial binder replacement, the control sample (0% CR) achieved strengths of 44.6 MPa at 7 days and 63.2 MPa at 28 days. At CR contents of 9.4%, 17.9%, and 25.5%, the 7-day compressive strengths decreased to 37.7, 32.9, and 31.3 MPa, corresponding to reductions of 15.47%, 26.23%, and 29.82%, respectively, compared to the control. At 28 days, strengths were 55.1, 43.5, and 38.0 MPa, reductions of 13.0%, 31.3%, and 40.0% (Figure 4B). Despite these reductions, AAS pastes outperformed OPC pastes at equivalent CR levels, particularly at 25.5%, likely due to the denser and more cohesive AAS matrix, which mitigates rubber matrix interfacial defects.

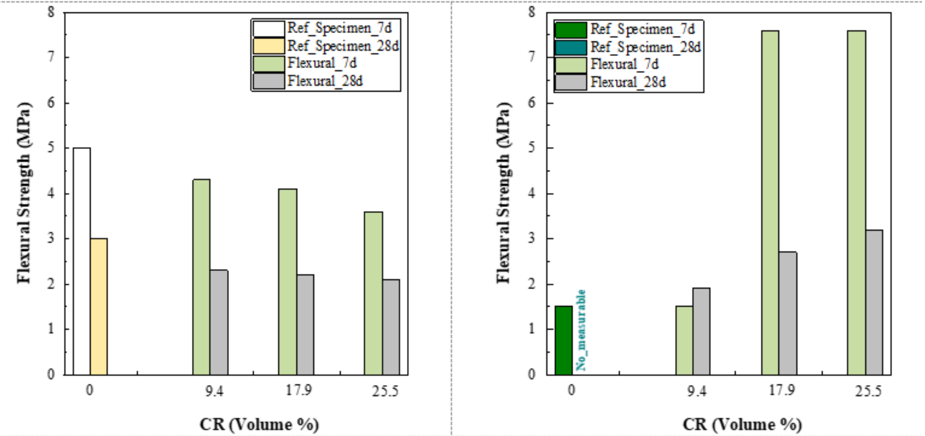
Flexural Strength of OPC and AAS Pastes with CR Partial Binder Replacement at 7 and 28 Days

For OPC paste (flexural strength) with CR as a partial binder replacement, the control sample (0% CR) recorded 5.0 MPa at 7 days and 3.0 MPa at 28 days. At CR contents



(A) 7- and 28- Day Compressive Strength of OPC Paste.

(B) 7 - and 28-Day Compressive Strength of AAS Paste.



(C) 7- and 28- Day Flexural Strength of OPC Paste.

(D) 7- and 28- Day Flexural Strength of AAS Paste.

Figure 4: Compressive and Flexural Strengths at 7 and 28 Days for OPC and AAS Pastes with Partial Binder Replacement by CR.oncrete

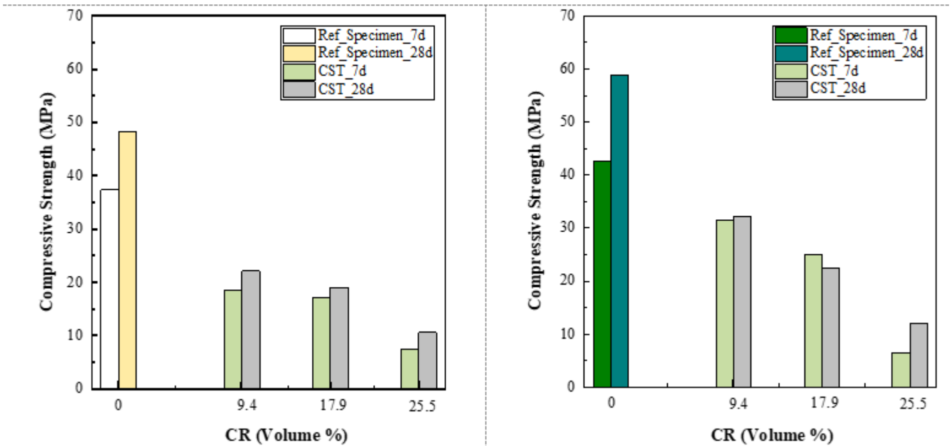
of 9.4%, 17.9%, and 25.5%, the 7-day flexural strengths decreased to 4.3, 4.1, and 3.6 MPa, corresponding to reductions of 14%, 18%, and 28%, respectively, compared to the control. At 28 days, strengths were 2.3, 2.2, and 2.1 MPa, reductions of 23.33%, 26.67%, and 30%, respectively (Figure 4C). For AAS paste (flexural strength) with CR as a partial binder replacement, the control sample (0% CR) exhibited a flexural strength of 1.5 MPa at 7 days, while no measurable strength was recorded at 28 days. With 9.4%, 17.9%, and 25.5% CR, 7-day strengths were 1.5, 7.6, and 7.6 MPa, changes of 0%, +406.7%, and +406.7% versus control. At 28 days, strengths were 1.9, 2.7, and 3.2 MPa; percentage changes relative to control are undefined because the control failed in flexure (no measurable strength). Overall, the flexural strength of AAS pastes increased with increasing CR content, indicating enhanced crack-bridging and energy dissipation effects associated with rubber particle incorporation (Figure 4D).

Compressive Strength of OPC and AAS Mortars with CR Partial Binder Replacement at 7 and 28 Days

For OPC mortar (compressive strength) with CR as a partial binder replacement, the control sample (0% CR) achieved compressive strengths of 37.4 MPa at 7 days and 48.3 MPa at 28 days. At CR contents of 9.4%, 17.9%, and 25.5%, the 7-day compressive strengths decreased to 18.6, 17.2, and 7.4 MPa, corresponding to reductions of 50.27%, 54.01%, and 80.21%, respectively, compared to the control. At 28 days, the compressive strengths were 22.1, 19.0, and 10.6 MPa, representing reductions of 54.24%, 60.66%, and 78.05%, respectively, compared to the control (Figure 5A). For AAS mortar, a similar decreasing trend in compressive strength was observed with increasing CR content; however, the reduction was comparatively less pronounced than in OPC mortar, indicating improved compatibility between CR and the AAS matrix (Figure 5B).

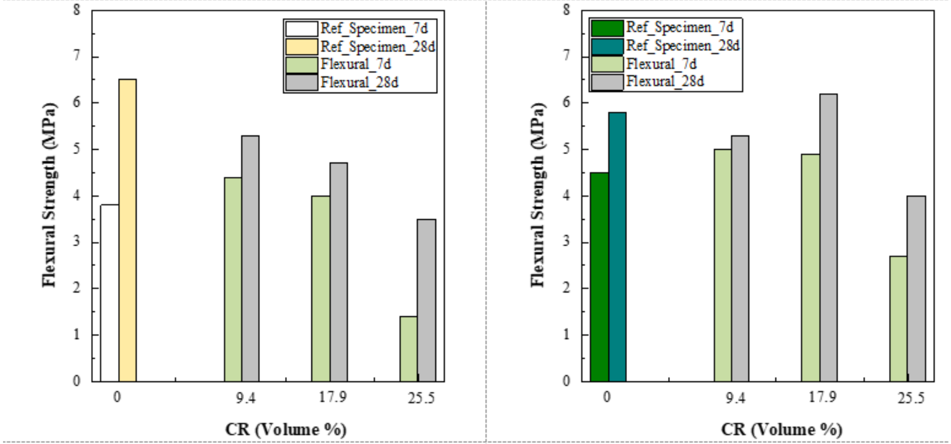
Flexural Strength of OPC and AAS Mortars with CR Partial Binder Replacement at 7 and 28 Days

For OPC mortar (flexural strength) with CR as a partial binder replacement, the control sample (0% CR) recorded 3.8 MPa at 7 days and 6.5 MPa at 28 days. At CR contents of 9.4%, 17.9%, and 25.5%, the 7-day flexural strengths changed to 4.4, 4.0, and 1.4 MPa, corresponding to variations of +15.8%, +5.3%, and -63.2%, respectively, compared to the control. At 28 days, strengths were 5.3, 4.7, and 3.5 MPa, reductions of 18.5%, 27.7%, and 46.2%, respectively (Figure 5C). For AAS mortar, moderate CR



(A) 7 and 28- day compressive strength of OPC mortar.

(B) 7 and 28-day compressive strength of AAS mortar.



(C) 7- and 28-day flexural strength of OPC mortar.

(D) 7- and 28- Day flexural strength of AAS mortar.

Figure 5: Compressive and flexural strength at 7 and 28 Days for OPC and AAS mortar with partial binder replacement by CR.

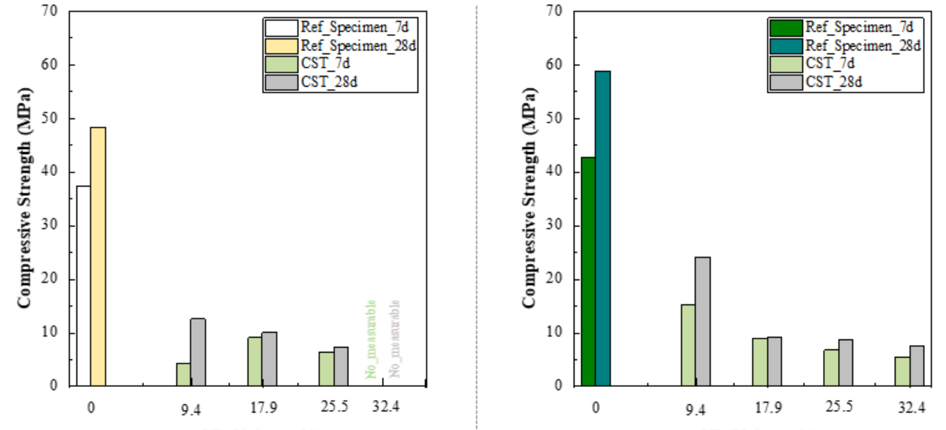
incorporation (9.4%-17.9%) slightly enhanced flexural strength, while higher CR content resulted in a decline. This behavior suggests that CR contributes to improved energy absorption and crack resistance at optimal levels but becomes detrimental at excessive dosages due to matrix disruption (Figure 5D).

Compressive Strength of OPC and AAS Mortars with CR Partial FA Replacement at 7 and 28 Days

For OPC mortar (compressive strength; CR as partial FA replacement), the control (0% CR) reached 37.4 MPa at 7 days and 48.3 MPa at 28 days. With 9.4%, 17.9%, 25.5%, and 32.4% CR, 7-day strengths were 4.4, 9.1, 6.5, and 0.0 MPa, reductions of 88.24%, 75.67%, 82.62%, and 100%, respectively. At 28 days, strengths were 12.6, 10.1, 7.4, and 0.0 MPa, reductions of 73.91%, 79.09%, 84.68%, and 100%, respectively. At the highest replacement level (32.4% CR), no measurable compressive strength was observed (Figure 6A). AAS mortar (compressive strength; CR as partial FA replacement), the control (0% CR) achieved 42.6 MPa at 7 days and 58.8 MPa at 28 days. With 9.4%, 17.9%, 25.5%, and 32.4% CR, 7-day strengths were 15.2, 8.9, 6.8, and 5.5 MPa, reductions of 64.3%, 79.1%, 84.0%, and 87.1%, respectively. At 28 days, strengths were 24.2, 9.2, 8.7, and 7.6 MPa. The significant reduction in compressive strength with increasing CR content is attributed to the hydrophobic nature of CR, poor interfacial bonding, and increased porosity, which weaken the load-bearing capacity of the matrix (Figure 6B).

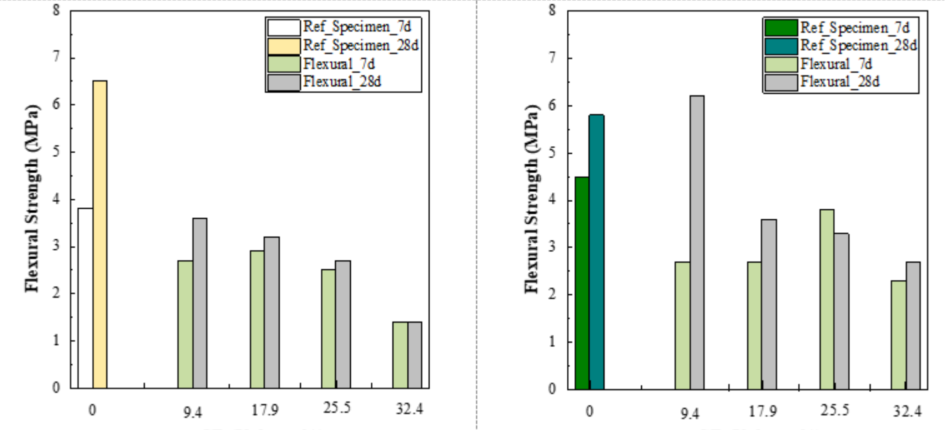
Flexural Strength of OPC and AAS Mortars with CR Partial FA Replacement at 7 and 28 Days

For OPC mortar (flexural strength; CR as partial FA replacement), the control (0% CR) measured 3.8 MPa at 7 days and 6.5 MPa at 28 days. With 9.4%, 17.9%, 25.5%, and 32.4% CR, 7-day strengths were 2.7, 2.9, 2.5, and 1.4 MPa, reductions of 29.0%, 23.7%, 34.3%, and 63.2%, respectively. At 28 days, strengths were 3.6, 3.2, 2.7, and 1.4 MPa, reductions of 44.6%, 50.8%, 58.5%, and 78.5%, respectively. Overall, the loss of flexural capacity increased with increasing CR content, with the smallest reductions observed at intermediate levels (9.4-17.9%) and the most significant decline at 32.4% (Figure 6C). For AAS mortar (flexural strength; CR as partial FA replacement), the control (0% CR) measured 4.5 MPa at 7 days and 5.8 MPa at 28 days. With 9.4%, 17.9%, 25.5%, and 32.4% CR, 7-day strengths were 2.7, 2.7, 3.8,



(A) 7 and 28- days compressive strength of OPC mortar.

(B) 7 and 28-day compressive strength of AAS mortar.



(C) 7- and 28- Day flexural strength of OPC mortar.

(D) 7-and 28- Day flexural strength of AAS mortar.

Figure 6: Compressive and flexural strength at 7 and 28 days for OPC and AAS mortar with partial FA replacement by CR.

and 2.3 MPa, reductions of 40.0%, 40.0%, 15.6%, and 48.9%, respectively. At 28 days, strengths were 6.2, 3.6, 3.3, and 2.7 MPa, changes of +6.9%, -37.93%, -43.10%, and -53.45%, respectively. Compared to AAS, OPC mortars exhibited slightly better flexural performance at intermediate CR contents (9.4-17.9%); however, both systems showed significant performance degradation at higher CR levels (32.4%) as illustrated in (Figure 6D).

Discussion

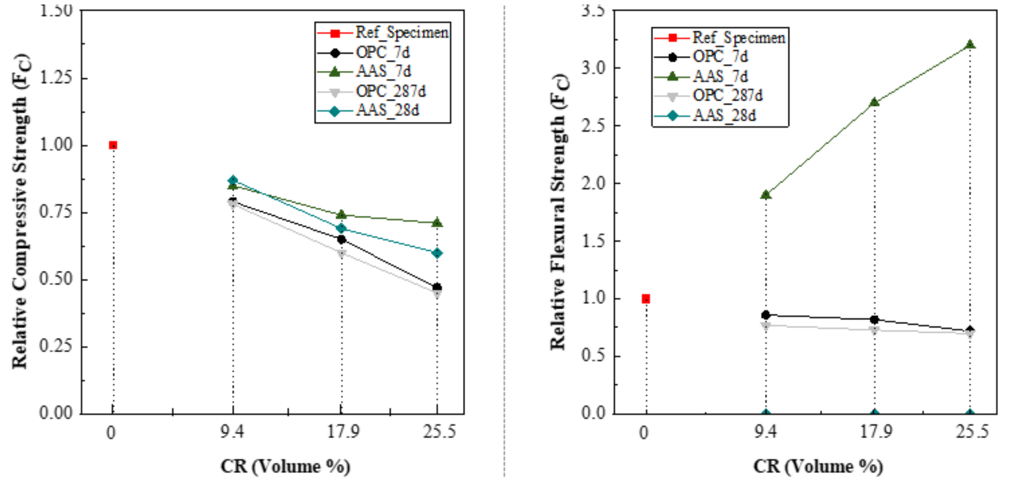
This study evaluates the mechanical performance of OPC and AAS mixtures, incorporating CR as a partial replacement for both binder and FA materials. The discussion focuses on the compressive strength and flexural strength properties of paste and mortar matrices at varying CR contents and curing ages, emphasizing the comparative behaviour and flexibility of each binder type.

Relative Compressive Strength of OPC and AAS Paste with Binder Partial Replaced by CR

In Ordinary Portland Cement paste, the control mix (0% CR) exhibited a normalized compressive strength of 1.00. The present study demonstrates that partial replacement of OPC with CR at 9.4%, 17.9%, and 25.5% (vol.%) results in a progressive decrease in compressive strength. At 28 days, the relative compressive strength for the same CR partial replacement levels was 0.78, 0.60, and 0.45. These findings are consistent with previous studies, which report that the incorporation of CR leads to reduced compressive strength due to weak interfacial bonding and the elastic nature of rubber particles. However, some studies have reported contrasting results, suggesting that the negative impact of CR can be mitigated through surface treatment, optimized particle size, or improved dispersion techniques. For instance, Silva *et al.* (2023) observed a similar trend in their investigation of CR as a partial replacement in cementitious materials. Additionally, Shahjalal *et al.* (2024) reported that, while early age strength was adversely affected, the long-term strength development showed improved performance due to enhanced microstructure. However, some studies have reported contrasting findings. Niş *et al.* (2023) found that certain processing methods or CR sizes could mitigate the negative impact on compressive strength. Furthermore Mohammed *et al.* (2022) highlighted that, the use of specific CR processing methods could reduce strength loss, especially at later curing stages. This discrepancy in results highlights the complexity of CR's influence on cementitious properties and underscores the need for further research to optimize CR incorporation in concrete mixtures. Agrawal *et al.* (2024) also found a reduction in compressive strength with higher CR content, supporting this study findings at both 7 and 28 days. Similarly, in alkali-activated slag paste, the control mix (0% CR) exhibited a relative compressive strength of 1.00. The present study found that partial replacement of the AAS binder with crumb rubber (CR) at 9.4%, 17.9%, and 25.5% (vol.%) led to a decrease in relative compressive strength (Fc) at 7 days to 0.85, 0.74, and 0.70, respectively. At 28 days, the relative compressive strength for the same CR replacement levels was 0.87, 0.69, and 0.60. These results align with previous studies that reported a reduction in compressive strength with increasing CR content. For instance, Elbaz *et al.* (2025) observed a similar trend in their investigation of CR as a partial replacement in cementitious materials. Additionally, Pradhan *et al.* (2024) noted that while early-age strength was adversely affected, the long-term strength development showed improved performance due to enhanced microstructure. However, some other studies have reported contrasting findings. Azunna *et al.* (2025) found that certain processing methods and CR sizes could mitigate the negative impact on compressive strength. This discrepancy highlights the complexity of CR's influence on cementitious properties and underscores the need for further research to optimize CR incorporation in concrete mixtures.as illustrated in Figure 7A.

Relative Flexural Strength of OPC and AAS Paste with Binder Partial Replaced by CR

In ordinary Portland cement paste (OPC-P), the control mix (0% CR) exhibited a relative flexural strength of 1.00. The present study found that partial replacement of the OPC binder with CR at 9.4%, 17.9%, and 25.5% (vol.%) led to a decrease in relative flexural strength (FF) at 7 days to 0.86, 0.82, and 0.72, respectively. At 28 days, the relative flexural strength for the same CR replacement levels was 0.77, 0.73, and 0.70. These results align with previous studies that reported a reduction in flexural strength with increasing CR content. For instance, Saad *et al.* (2024) explained a similar trend in their investigation of CR as a partial replacement in OPC materials. Additionally, Li *et al.* (2025) noted that while early age strength was adversely affected, the long-term strength development showed improved performance due to enhanced microstructure. However, some studies have reported contrasting findings. Parama *et al.* (2022) found that, certain processing methods or CR sizes could mitigate the negative impact on flexural strength. furthermore, highlighted that the use of specific CR processing methods could reduce strength loss, especially at later curing stages. This discrepancy in results highlights the complexity of CR's influence on cementitious properties and underscores the need for further research to optimize CR incorporation in concrete mixtures. Similarly, in alkali-activated slag-based paste (AAS-P), the control mix (0% CR) exhibited a relative flexural strength of 1.00. The present study found that partial replacement of AAS binder with crumb rubber (CR) at 9.4%, 17.9%, and 25.5% (vol.%) outstanding increased the relative flexural strength (FF) at 7 days to 1.00, 5.07, and 5.07, respectively. At 28 days, the control mix showed no result, but increasing CR content corresponded to higher flexural strength were observed. This enhancement can be attributed to the superior bonding characteristics of AAS matrices, where the dense geopolymeric gel structure facilitates better stress transfer and enhances crack-bridging effects provided by CR particles. With recent studies that have explored the incorporation of CR into AAS composites. For instance, Elbaz *et al.* (2025) investigated the partial replacement of copper slag with treated CR aggregates in alkali-activated slag mortar and observed improvements in mechanical properties, including flexural strength. Also, Saad *et al.* (2024) examined that alkali-activated slag and OPC-based composites containing CR aggregates and reported enhanced mechanical and durability properties, which aligns with the observed increase in flexural strength in the present study. However, it is important to note that while CR incorporation can enhance certain mechanical properties, the absence of a result for the control mix at 28 days in this study suggests that the interaction between CR and AAS binders may be complex and warrants further investigation. Understanding the underlying mechanisms, such as the role of CR in microstructural development and its interaction with alkali activators, is crucial for optimizing the use of CR in AAS composites. As illustrated in Figure 7B.



(A) RCS at 7-and 28-days (B) RFS at 7-and 28-days.

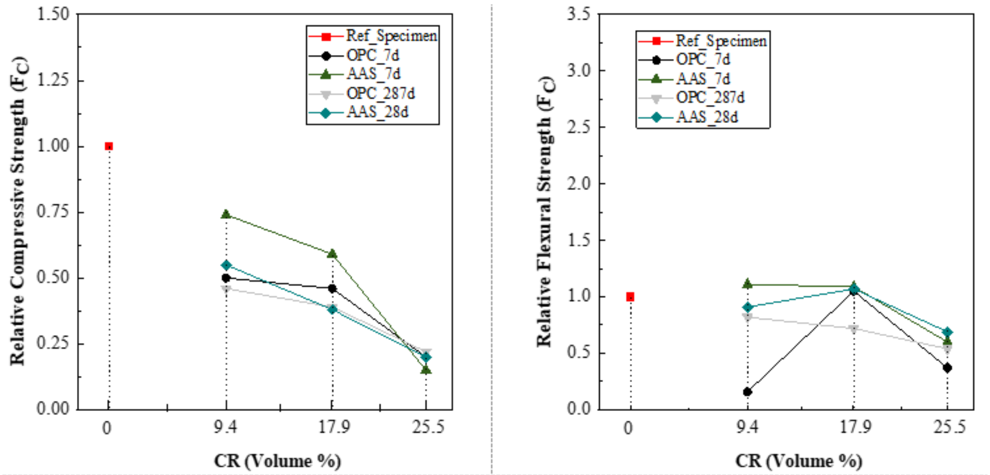
Figure 7: OPC and AAS paste with partial replaced of binder materials by CR.

Relative Compressive Strength of OPC and AAS Mortar with Binder Partial Replaced of by CR

In ordinary Portland cement mortar (OPC-M), the control mix (0% CR) exhibited a relative compressive strength of 1.00. This study found that partial replacement of the OPC binder with CR at 9.4%, 17.9%, and 25.5% (vol.%) reduced the relative compressive strength (Fc) at 7 days to 0.50, 0.46, and 0.20, respectively. At 28 days, the relative compressive strength for the same CR partial replacement levels was 0.46, 0.39, and 0.22. The observed reduction in compressive strength with increasing CR content in OPC mortar is consistent with previous studies and is primarily attributed to increased porosity and weak interfacial transition zones (ITZs) between CR and the cement matrix. indicating that incorporating CR into OPC binder materials generally leads to a decrease in compressive strength. For instance, Li *et al.* (2025) observed a reduction in compressive strength by 10 to 26% after 7 days of curing for concrete containing CR at 2.5 to 10% content. Also, Parama *et al.* (2022) reported that, a decrease in compressive strength from 15.3 MPa to 10.9 MPa with increasing CR content from 5% to 8%. Similarly, in alkali activated slag mortar (AAS-M), the control mix (0% CR) exhibited a relative compressive strength of 1.00. This study found that partial replacement of the OPC binder with CR at 9.4%, 17.9%, and 25.5% (vol.%) reduced the relative compressive strength (Fc) at 7 days to 0.74, 0.59, and 0.15, respectively. At 28 days, the relative compressive strength for the same CR replacement levels was 0.55, 0.39, and 0.21. The observed reduction in compressive strength with increasing CR content in OPC mortar is consistent with previous studies and is primarily attributed to increased porosity and weak interfacial transition zones (ITZs) between CR and the cement matrix. indicating that incorporating CR into OPC binder materials generally leads to a decrease in compressive strength. For instance, Lim *et al.* (2022) observed a reduction in compressive strength by 10 -26% after 7 days of curing for AAS based mortar containing CR at 2.5 -10% content. In meanwhile, Elbaz *et al.* (2025) demonstrated that a decrease in compressive strength from 15.3 MPa to 10.9 MPa with increasing CR content from 5% to 8%. As illustrated in Figure 8A.

Relative Flexural Strength of OPC and AAS Mortar with Binder Partial Replaced by CR

In ordinary Portland cement mortar (OPC-M), the control mix (0% CR) exhibited a relative flexural strength of 1.00. This study found that partial replacement of the OPC binder with CR at 9.4%, 17.9%, and 25.5% (vol.%) increased the relative flexural strength (FF) at 7 days to 1.16, 1.05, and decreased to 0.37, respectively. At 28 days, the relative flexural strength for the same CR partial replacement levels was 0.82, 0.72, and 0.54. These findings are consistent with recent studies indicating that incorporating CR into OPC binder materials generally leads to an increase in flexural strength. For instance, Onuaguluchi *et al.* (2019) observed that improvements in flexural strength with increasing CR content in cement mortar, particularly when surface pre-coating and silica fume were utilized to enhance the CR cement matrix interface. Similarly, Adamu *et al.* (2022) reported that decrease in flexural strength with higher CR content. These previous studies supporting these findings for both 7 and 28 days. Similarly, in alkali activated mortar (AAS-M), the control mix (0% CR) exhibited a relative flexural strength of 1.00. The study found that partial replacement of the AAS binder with CR at 9.4%, 17.9%, and 25.5% (vol.%) increased the relative flexural strength (FF) at 7 days to 1.11, 1.09, and decreased to 0.6, respectively. At 28 days, the relative flexural strength for the same CR replacement levels was reduced to 0.91, 0.07, and 0.69. These findings are consistent with recent studies indicating that incorporating CR into alkali-activated slag-based materials can influence mechanical properties. Also, Ameri *et al.* (2024) investigated the partial replacement of copper slag with treated CR aggregates in alkali-activated slag mortar and observed enhancements in mechanical properties, including flexural strength. Similarly, Nematzadeh *et al.* (2021) examined that the effect of CR on the flexural strength and reported enhanced its mechanical performance including flexural strength with the partial replacement of CR. As illustrated in Figure 8B. However, at higher CR contents, the flexural strength decreases due to excessive void formation and reduced matrix continuity, which compromise load transfer efficiency.



(A) RCS at 7-and 28-days.

(B) RFS at 7-and 28-days.

Figure 8: OPC and AAS mortar with partial replaced of binder by CR.

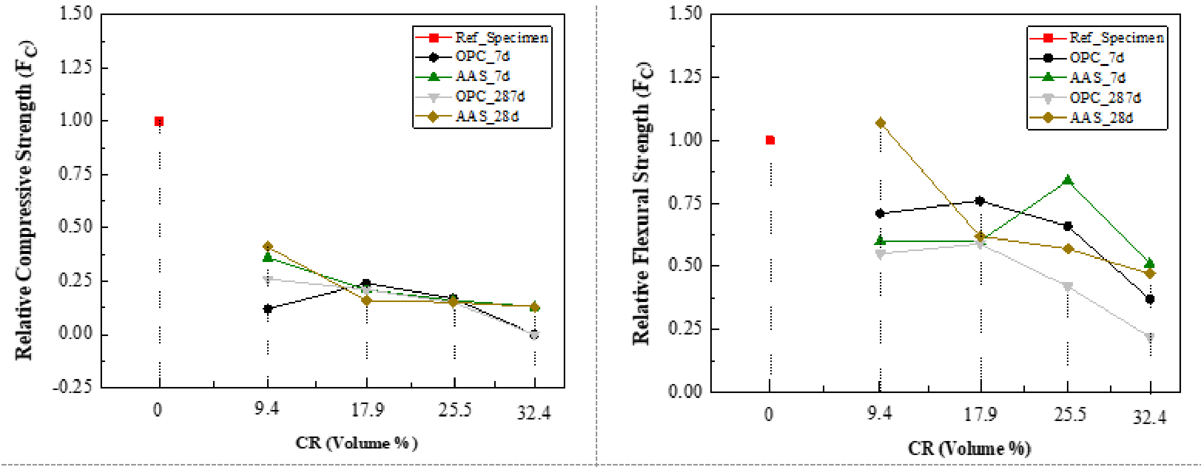
Relative Compressive Strength of OPC and AAS Mortar with FA Partial Replaced by CR

In ordinary Portland cement mortar (OPC-M), the control mix (0% CR) exhibited a relative compressive strength of 1.00. The study found that partial replacement of FA with CR at 9.4%, 17.9%, 25.5%, and 32.5% (vol.%) outstanding reduced the relative compressive strength (Fc) at 7 days to 0.12, 0.24, 0.17, and 0.00, respectively. At 28 days, the relative compressive strength for the same CR replacement levels was 0.26, 0.21, 0.15, and 0.00. Notably, no compressive strength was observed at a 35.5% CR partial replacement for either curing age. These findings align with recent studies indicating that incorporating CR into cementitious materials generally leads to a decrease in compressive strength. Siregar *et al.* (2023) observed that the significant deterioration in compressive strength with CR as fine aggregate replacement is primarily due to the hydrophobic surface of CR, which limits bonding with the matrix, and the increased void content that reduces structural integrity with increasing CR content in OPC based mortar. Similarly, Alamri *et al.* (2024) reported that decrease in compressive strength with higher CR content, which is supporting this research findings at both 7 and 28 days. Similarly, in alkali activated slag mortar (AAS-M), the control mix (0% CR) exhibited a relative compressive strength of 1.00. The study found that partial replacement of FA with CR at 9.4%, 17.9%, 25.5%, and 32.5% (vol.%) reduced the relative compressive strength (Fc) at 7 days to 0.36, 0.21, 0.16, and 0.13, respectively. At 28 days, the relative compressive strength for the same CR partial replacement levels was 0.42, 0.16, 0.15, and 0.13 observed respectively. These findings align with recent studies indicating that incorporating CR into alkali-activated slag-based materials can influence mechanical properties. Fu *et al.* (2022) observed that the significant deterioration in compressive strength with CR as fine aggregate replacement is primarily due to the hydrophobic nature surface of CR, which limits bonding with the matrix, and the increased void content that reduces structural integrity. with increasing CR content in alkali-activated matrixes, attributing this to the weak bonding between CR particles and the alkali-activated matrix. Elbaz *et al.*

(2025) reported that decrease in compressive strength with higher CR content in rubberized alkali-activated matrix, supporting these findings at both 7 and 28 days. As illustrated in Figure 9A.

Relative Flexural Strength of OPC and AAS Mortar with FA Partial Replaced by CR

In ordinary Portland cement mortar (OPC-M), the control mix (0% CR) exhibited a relative flexural strength of 1.00. The study found that partial replacement of FA with CR at 9.4%, 17.9%, 25.5%, and 32.5% (vol.%) decreased the relative flexural strength (FF) at 7 days to 0.71, 0.76, 0.66, and 0.37, respectively. At 28 days, the relative flexural strength for the same CR replacement levels was 0.55, 0.49, 0.42, and 0.22. These findings align with recent studies indicating that incorporating CR into cementitious materials can influence mechanical properties. Kilani *et al.* (2025) reported that reduction in flexural strength with increasing CR content in cement mortar, attributing this to the weak bonding between CR particles and the cement matrix. Similarly, Shahjalal *et al.* (2024) reported a decrease in flexural strength with higher CR content in recycled aggregate concrete, supporting this research findings at both 7 and 28 days. The reduction in flexural strength is attributed to several factors. First, the weak bonding between CR particles and the cement matrix can compromise the overall strength of the mortar. Second, the inclusion of CR can increase the porosity of the mix, leading to a less dense microstructure. Third, the hydrophobic nature of CR may hinder proper hydration of the cementitious materials, further affecting strength development. Similarly, in alkali-activated slag mortar (AAS-M), the control mix (0% CR) exhibited a relative flexural strength of 1.00. The study found that partial replacement of fine aggregates with crumb rubber (CR) at 9.4%, 17.9%, 25.5%, and 32.5% (vol.%) decreased the relative flexural strength (FF) at 7 days to 0.60, 0.60, 0.84, and 0.51, respectively. At 28 days, the relative flexural strength for the same CR partial replacement levels increased to 1.07, and decreased to 0.62, 0.57, and 0.47, respectively. These findings align with recent studies indicating that incorporating CR into alkali-activated slag-based materials can influence mechanical properties. Rakhimova *et al.* (2019) demonstrated that reduction in flexural strength with increasing CR content in alkali-activated slag mortar, attributing this to the weak bonding between CR particles and the alkali-activated matrix. Similarly, Azunna *et al.* (2025) reported that decrease in flexural strength with higher CR content in mortar, these finding supporting this study at both 7 and 28 days. The reduction in flexural strength is attributed to several factors. First, the weak bonding between CR particles and the cement matrix can compromise the overall strength of the mortar. Second, the inclusion of CR can increase the porosity of the mix, leading to a less dense microstructure. Third, the hydrophobic nature of CR may hinder proper hydration of the cementitious materials, further affecting strength development. As illustrated in Figure9B.



(A) RCS at 7-and 28-days. (B) RFS at 7-and 28-days.

Figure 9: OPC and AAS mortar with partial replaced FA by CR.

Comparative Study of OPC and AAS Paste and Mortar Mixes

A direct comparison between OPC and AAS mixes is not appropriate due to their differing chemical compositions. However, in this study, a brief comparison is provided based on construction binder materials. OPC and AAS binders have different chemical compositions and structures, making direct comparison challenging. However, this study explored the use of AAS as an alternative to OPC in construction, as paste and mortar properties significantly affect concrete performance. AAS matrices exhibited higher compatibility with CR compared to OPC, due to differences in pore structure, alkalinity, and chemical reactions. As the results showed that AAS-CR composites offer better flexural performance than OPC-CR composites. Despite this, CR incorporation in both binders leads to strength reductions, particularly at higher CR contents (typically >17.9-25.5% by volume), as CR's flexibility and hydrophobicity impair matrix bonding and promote void formation. This study highlights the superior compressive strength retention of AAS binders over OPC at all levels of CR replacement. This enhanced performance is attributed to the denser pore structure and superior mechanical flexibility of AAS, which allows for greater tolerance to CR induced weaknesses. While AAS mixes showed less predictable flexural strength, especially in paste form, they demonstrated promising resilience under varying conditions. In contrast, OPC mixes showed more consistent but generally lower flexural strength. Similar findings were reported by Bernal *et al.* (2011). Thus, AAS binders are more suitable for CR incorporation in compressive strength applications, while OPC offers better control over flexural performance, as shown in Table.3. Overall, the comparative analysis demonstrates that AAS-based systems exhibit superior compatibility with CR compared to OPC-based systems. This is primarily attributed to the dense geopolymeric matrix, enhanced interfacial bonding, and improved stress distribution mechanisms in AAS. While CR incorporation generally leads to reductions in compressive strength, it contributes positively to ductility and energy absorption. Therefore, optimizing CR content is essential to balance mechanical performance and sustainability benefits in cementitious materials.

Table 3: The influence of CR content on compressive strength and flexural strength in OPC and AAS-based pastes and mortars.

Mixture type	**CR partial replaced level (volume %)**	**Compressive Strength**		**Flexural Strength**	
		At 7- Day (%)	**At 28-Day (%)**	**At 7- Day (%)**	**At 28-Day (%)**
OPC based paste partial binder replacement by CR	9.4	-11.8	-21.9	-14.0	-23.33
	17.9	-34.9	-40.3	-18.0	-26.6
	25.5	-53.5	-54.9	-28.0	-30.0
OPC based mortar /partial binder replacement by CR	9.4	-50.27	-54.24	+15.8	-18.5
	17.9	-54.01	-60.66	+5.3	-27.7
	25.5	-80.21	-78.05	-63.2	-46.2
OPC based mortar / partial FA replacement by CR	9.4	-88.24	-73.91	-29.0	-44.6
	17.9	-75.67	-79.09	-23.7	-50.8
	25.5	-82.62	-84.68	-34.3	-58.5
	32.4	-100	-100	-63.2	-78.5
AAS based paste partial binder replacement by CR	9.4	-15.47	-13.0	0	No measurable
	17.9	-26.23	-31.3	+406.7	No measurable
	25.5	-29.82	-40.0	+406.7	No measurable
AAS based mortar /partial binder replacement by CR	9.4	-25.8	-45.2	+11.1	-8.6
	17.9	-41.1	61.7	+8.9	+6.9
	25.5	-84.7	-79.6	-40.0	-31.0
	9.4	-64.3	-58.84	-40.0	+6.9
AAS based mortar / partial FA replacement by CR	17.9	-79.1	-84.35	-40.0	-37.93
	25.5	-84.0	-85.20	-15.6	-40.10
	32.4	-87.1	-87.1	-48.9	-53.45

For normalization, 0% CR controls were set to 100% at each age. Pastes: OPC, 41.5/57.6 MPa (7/28 d) compressive; 5.0/3.0 MPa flexural. AAS, 44.6/63.2 MPa compressive; 1.5/0.0 MPa flexural (28-day flexural normalization undefined). Mortars: OPC, 37.4/48.3 MPa compressive; 3.8/6.5 MPa flexural. AAS, 42.6/58.8 MPa compressive; 4.5/5.8 MPa flexural. (Mortar control values apply to both CR-as-binder and CR-as-fine-aggregate replacement modes). In subsequent comparisons, (+) denotes a percentage increase relative to the respective baseline, (–) denotes a decrease, and (×) indicates that a test was not conducted.

CONCLUSION

This study presents a comprehensive experimental comparison of the mechanical performance of CR in OPC and AAS-based pastes and mortars. The findings show that increasing CR content leads to a consistent reduction in compressive strength in both mixtures, primarily due to weak interfacial bonding and increased porosity. However, moderate CR incorporation (9.4-17.9%) contributes to improved flexural strength and ductility, highlighting its potential for enhancing energy absorption and toughness. AAS-based mixtures exhibited superior compatibility with CR compared to OPC, showing better strength retention and enhanced flexural behavior. This improved performance is attributed to the dense geopolymeric matrix and stronger interfacial interactions in AAS, which facilitate more effective stress transfer and crack resistance. Nevertheless, excessive CR content (25.5%) significantly deteriorates mechanical properties, specifically when used as a fine aggregate partial replacement, indicating that careful optimization of CR dosage is essential. Overall, the findings highlight the potential of AAS-CR composites as sustainable construction materials with improved ductility and environmental benefits. Future research should focus on surface modification of CR, optimization of mix design, and long-term durability performance to further enhance the applicability of rubberized cementitious mixtures, and also these findings provide a valuable framework for the development of sustainable, high-performance rubberized cementitious materials in future construction applications.

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