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# Effect of Waste Glass Powder Particle Size on Flow and Compressive Strength of Slag-Based Alkali-Activated Materials

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## ABSTRACT

This study investigates the effect of waste glass powder particle size on the flow and compressive strength of slag-based alkali-activated mortar. Ground granulated blast-furnace slag was partially replaced with waste glass powder at 10%, 20%, and 30% by mass. Three waste glass powder particle-size ranges were considered: <75 µm, 75–150 µm, and 150–300 µm. A control mixture containing 100% slag was also prepared. All mixes were activated using 12 M sodium hydroxide and sodium silicate solution, with a sodium silicate-to-sodium hydroxide ratio of 0.6 and a binder-to-alkaline activator ratio of 2.5. The fresh properties were evaluated using a flow table test, while compressive strength was experimental at 7 and 28 days using three specimens per mix. The experimental results indicate that finer waste glass powder reduced flow because of its higher surface area, while coarser waste glass powder improved flow but reduced compressive strength. The highest experimental 28-day compressive strength was obtained by the mix containing 80% slag and 20% waste glass powder below 75 µm, reaching 72.0 MPa, which was 10.8% higher than the 100% slag control. Overall, the results suggest that moderate replacement of slag with fine waste glass powder can improve strength, but excessive replacement or coarser particle size may reduce

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mechanical performance.

**Keywords:** Waste Glass Powder; Particle Size; Slag; Alkali-Activated Materials; Sodium Hydroxide; Sodium Silicate; Flow; Compressive Strength; Sustainable Mortar.

## Introduction

In slag-based alkali-activated materials, waste glass powder can act as both a filler and a reactive silica source. Its particle size matters because it changes how fast the glass dissolves, how densely the binder packs, and how the fresh and hardened material behave[1], [2].

Slag-based alkali-activated materials use ground granulated blast-furnace slag as the main binder and an alkaline solution to trigger reaction and hardening. In these systems, waste glass powder is often studied as a partial replacement for slag because it is rich in amorphous silica, is widely available as a waste stream, and can help lower raw-material use and waste disposal. The key issue is that waste glass does not behave the same at all sizes: very fine particles have higher surface area, dissolve more easily in alkaline media, and can join the reaction more than coarse particles, while coarser particles tend to act more like inert filler[3]. Because of this, particle size can strongly affect fresh-state flow, setting, gel formation, pore structure, and later compressive strength. In practice, the effect of glass powder size must be judged together with replacement level, activator type and concentration, liquid-to-binder ratio, and curing conditions, since these factors control whether the glass mainly improves packing or meaningfully reacts in the slag-based matrix [1], [4], [5], [6], [7], [8], [9].

Alkali-activated materials are increasingly studied as alternative binders to ordinary Portland cement because they can use industrial by-products and waste-based aluminosilicate materials[10], [11], [12], [13], [14]. Ground granulated blast-furnace slag is one of the most reactive precursors in alkali-activated systems because its calcium-rich composition supports the formation of C-A-S-H and C-(N)-A-S-H type reaction products, which are closely linked with strength development[15], [16], [17], [18], [19], [20]. Sodium hydroxide and sodium silicate are commonly used activators in geopolymer and alkali-activated binders because they enhance precursor dissolution and gel formation[21], [22], [23], [24], [25]. Waste glass powder is also a promising material in alkali-activated systems because soda-lime glass contains a high amount of amorphous silica. When it is ground into powder, it may behave partly as a filler and partly as a reactive silica source. Previous studies have shown that WGP can improve the properties of alkali-activated binders when used at suitable replacement levels.One recent study reported that replacing 20% of GGBS with WGP produced the highest compressive strength, while higher WGP replacement caused strength reduction. However, the effect of WGP depends strongly on its particle size. Fine particles can dissolve more easily in alkaline solution and may improve particle packing, but they can also reduce flow because of higher surface area[26], [27], [28]. Coarser WGP particles may improve workability, but they are less reactive and may remain as weak filler particles in the hardened matrix. Recent research has also shown that WGP can promote a denser silica-rich gel matrix in alkali-activated concrete, supporting the idea that glass powder can be useful when properly proportioned[29], [30], [31], [32], [33], [34].

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This study therefore focuses on the effect of three WGP particle-size ranges, <75 µm, 75–150 µm, and 150–300 µm, on the flow and compressive strength of slag-based alkali-activated mortar.

## Materials and Methods

### Materials

The main binder used in this study was **ground granulated blast-furnace slag (GGBS)**. The particle density of GGBS was taken as **2980 kg/m³**, corresponding to a specific gravity of **2.98**. The slag was used in powder form, with a fine particle size suitable for alkali-activated binder production. If measured particle-size data are available, the slag fineness or average particle size should be reported in this section.

**Waste glass powder (WGP)** was used as a partial replacement for slag. The waste glass was crushed, ground, and sieved into three particle-size ranges: **(1) fine WGP (F): <75 µm; (2) medium WGP (M) : 75–150 µm; and (3) coarse WGP (C): 150–300 µm**. The particle density of WGP was taken as **2500 kg/m³**, which is typical for soda-lime glass powder. These particle-size ranges were selected to evaluate the influence of WGP fineness on the fresh and hardened properties of slag-based alkali-activated materials. The alkaline activator was prepared using **12 M sodium hydroxide solution** and commercial **sodium silicate solution**. The sodium silicate-to-sodium hydroxide ratio was kept constant at **0.6** for all mixtures.

The oxide composition presented in **Table 1** is a representative XRF composition based on typical GGBS and soda-lime WGP values reported in the literature. These values should be replaced with actual XRF results after testing. Previous studies have reported that GGBS is mainly rich in **CaO and $SiO_2$**, while soda-lime waste glass is mainly composed of **$SiO_2$, $Na_2O$, and CaO**.

**Table 1**. XRF oxide composition of slag and waste glass powder.

| Material | $SiO_2$ | $Al_2O_3$ | CaO | $Na_2O$ | $Fe_2O_3$ | $K_2O$ | MgO |
|---|---|---|---|---|---|---|---|
| Slag/GGBS | 31.17 | 13.92 | 55.85 | 0.63 | 0.73 | 0.42 | 0.67 |
| Waste glass powder | 71.79 | 3.57 | 6.81 | 11.05 | 0.52 | 0.53 | 1.22 |

### Mix Design

For the 1 m³ mix design, the following assumptions were used:
Total binder = 500 kg/m³
Fine aggregate/sand =2
Molarity NaOH concentration 12M
alkaline activator to Binder ratio = 0.6
Total alkaline activator = 338 kg/m³
SS/SH = 2.5

**Table 2.** Mix design for 1 m³ alkali-activated mortar.

| Mix ID | WGP size (µm) | Slag | WGP | Slag | WGP | Sand | NaOH | Sodium silicate | Extra water |
|---|---|---|---|---|---|---|---|---|---|
| | | (%) | | (kg/m³) | | | | | |
| S100 | Control | 100 | 0 | 563 | 0 | 1126 | 96.51 | 241.29 | 169 |

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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| F10 | <75 | 90 | 10 | 507 | 56 | 1126 | 96.51 | 241.29 | 169 |
| F20 | <75 | 80 | 20 | 450 | 113 | 1126 | 96.51 | 241.29 | 169 |
| F30 | <75 | 70 | 30 | 394 | 169 | 1126 | 96.51 | 241.29 | 169 |
| M10 | 75–150 | 90 | 10 | 507 | 56 | 1126 | 96.51 | 241.29 | 169 |
| M20 | 75–150 | 80 | 20 | 450 | 113 | 1126 | 96.51 | 241.29 | 169 |
| M30 | 75–150 | 70 | 30 | 394 | 169 | 1126 | 96.51 | 241.29 | 169 |
| C10 | 150–300 | 90 | 10 | 507 | 56 | 1126 | 96.51 | 241.29 | 169 |
| C20 | 150–300 | 80 | 20 | 450 | 113 | 1126 | 96.51 | 241.29 | 169 |
| C30 | 150–300 | 70 | 30 | 394 | 169 | 1126 | 96.51 | 241.29 | 169 |

**Preparation of Alkaline Activator**

Sodium hydroxide solution with a concentration of 12 M was prepared by dissolving sodium hydroxide pellets in water. Because the dissolution of sodium hydroxide releases heat, the solution was allowed to cool before use. The sodium hydroxide solution was then mixed with sodium silicate solution according to the fixed SS/SH ratio of 2.5 and AA/B 2.5.

**Mixing, Casting, and Curing**

The slag, WGP, and sand were first dry-mixed until a uniform mixture was obtained. The alkaline activator was then added gradually and mixing continued until the mortar became homogeneous. The fresh mortar was immediately tested for flow.

For compressive strength, mortar specimens were cast in cube moulds. The specimens were compacted properly to reduce entrapped air. After casting, the moulds were covered to prevent moisture loss. The specimens were demoulded after 24 hours and cured until the testing ages of 7 days and 28 days.

The flow test was based on the principle of ASTM C1437, which is used to determine the flow of hydraulic cement mortars and other cementitious mortars. Compressive strength testing was based on ASTM C109/C109M, which covers compressive strength testing of mortar using 50 mm cube specimens.

**Results and Discussion**

**Flow Results**

The experimetal flow results show that the flow decreased when fine WGP was used as illustrae in **Figure 1**. The control mix had an average flow of 175 mm, while the F30 mix had a experimental flow of only 150 mm. This reduction is mainly related to the high surface area of fine glass powder. Finer particles require more liquid for wetting, and this makes the fresh mortar more viscous. The opposite trend was experimental for the coarser WGP mixes. The C30 mix showed the highest experimental flow of 200 mm, which was 14.3% higher than the control. This happened because coarse WGP particles have lower surface area and behave more like filler than reactive powder. However, higher flow does not automatically mean higher strength. Waste glass powder often improves flow in slag-based alkali-activated mixes when it is coarser than the slag

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or finer additives it replaces, and this effect usually becomes stronger as glass content rises. But flow does not always increase: when glass is fine, has high surface area, or replaces a precursor with different packing and water demand, the paste can become stiffer and more viscous.

In slag-based alkali-activated materials, the fresh-state effect of waste glass powder is mainly a particle-packing and water-demand effect rather than a strong early-reaction effect. Several studies report that adding or increasing glass powder improves workability: ground glass improved mortar fluidity, and this was linked to favorable fresh-state behavior while later strength could recover with age[4]. In alkali-activated slag, slump flow increased slightly as glass powder replacement increased; at 20% replacement, slump flow rose from 27.2 to 29.1 cm, and the authors noted that waste glass benefited workability while silica fume reduced it, partly because the glass was much coarser (D50 about 20 μm versus about 11 μm for silica fume)[35]. A broader review makes the same point: compared with finer, higher-surface-area precursors such as metakaolin, glass powder tends to need less liquid for wetting because of its larger particle size and smaller surface area, so more free water remains for flow; similar improvement was also noted when glass powder replaced slag at up to 40% in alkali-activated materials[2]. More generally, around 20% replacement is often considered workable, but the benefit depends on the glass size, angularity, and surface area[5]. Related studies with glass cullet also show that replacing natural or crushed sand can maintain or slightly improve mortar flowability, even though those mixes are not the same as powder-for-slag replacement systems[36], [37]. At the rheology level, this same trend appears as lower yield stress and lower plastic viscosity when glass powder acts as a relatively less demanding solid phase. Li et al. found that in alkali-activated slag paste, increasing GP content decreased both yield stress and plastic viscosity[38].This is consistent with the idea that, when glass particles are not extremely fine, they can dilute the highly reactive slag fraction, reduce interparticle friction, and leave more liquid available for lubrication of the paste[2], [35]. Camargo et al. also showed that particle size distribution matters to processing: even when the extent of alkali activation did not change much, a coarser and narrower precursor size distribution altered viscosity and enlarged the workable processing window, highlighting that size distribution governs packing and fresh-state resistance to flow[39].

However, the direction of the flow change is not universal. Chen et al. reported the opposite trend in alkali-activated materials when GP replaced fly ash: fluidity decreased as GP content increased, while shear stress and equivalent plastic viscosity increased, and the paste shifted from shear-thinning toward shear-thickening behavior; at 20% GP replacement, fluidity dropped 15.3%, yield shear stress rose 49.6%, and viscosity rose 32.1% . This contrast shows why particle size must be read together with what the glass replaces. If GP is finer than the replaced precursor, has a broad or poorly packed grading, or raises surface area enough to tie up liquid, it can reduce flow instead of improving it[6]. So, for slag-based systems specifically, the most common pattern is a modest increase in flow with increasing waste glass powder content when the glass is coarser than the slag or much coarser than silica fume, but this benefit weakens or can reverse as the powder becomes finer or as replacement changes the packing and liquid

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demand of the full binder blend.

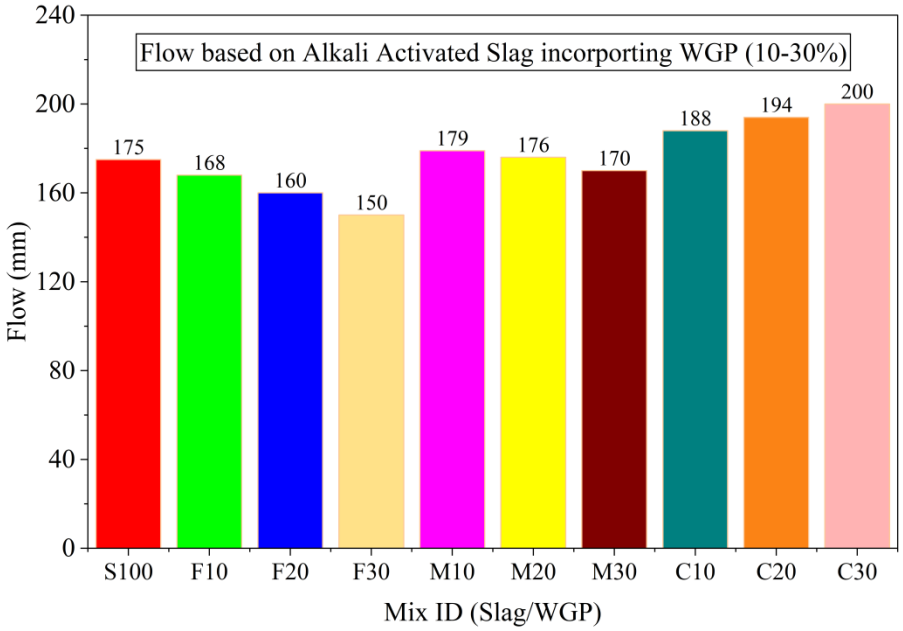


**Figure 1.** Flow of Alkali activated slag based

3.2 Compressive Strength

**Figure 2** and **Figure 3** show the 7 and 28 days compressive strenght of alkali activated materiasl. days At 7 days, the highest experimental compressive strength was obtained by F20, with an average strength of 54.0 MPa. This is 8.0% higher than the control. The improvement may be due to the fine WGP improving particle packing and supplying additional reactive silica in the alkaline environment. However, the F30 mix showed lower strength than F20. This suggests that replacing too much slag with WGP can reduce early-age strength. Slag is highly reactive and calcium-rich, so excessive replacement reduces the amount of calcium available for early reaction-product formation. This is consistent with previous findings where moderate WGP replacement improved strength, but higher replacement levels reduced compressive strength.

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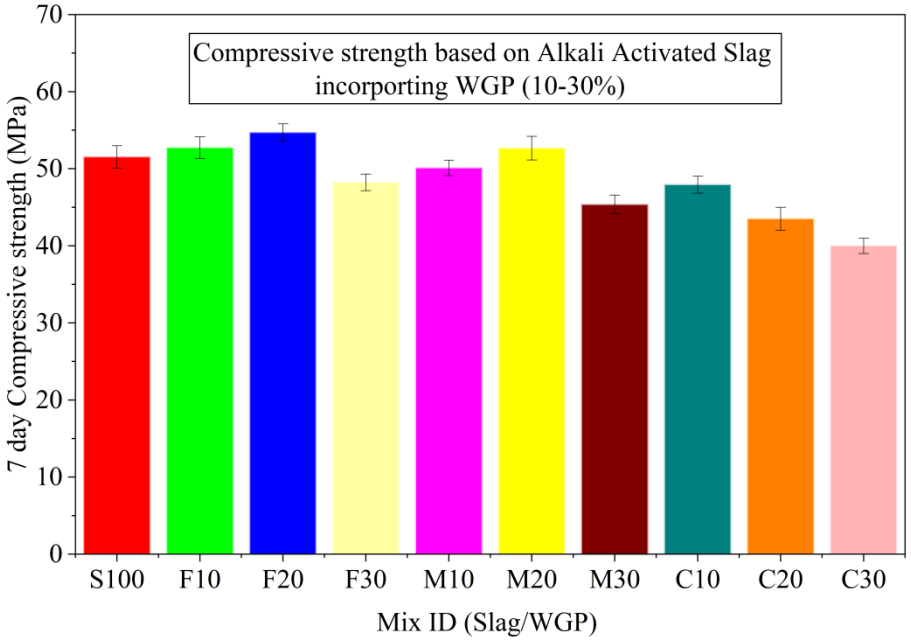


**Figure 2.** 7 days Compressive strength of Alkali activated slag based.

At 28 days, the experimental strength followed a similar trend to the 7-day results. The best-performing mix was again F20, which achieved a experimental average compressive strength of 72.0 MPa. This was 7.0 MPa higher than the control mix and represented a 10.8% improvement.

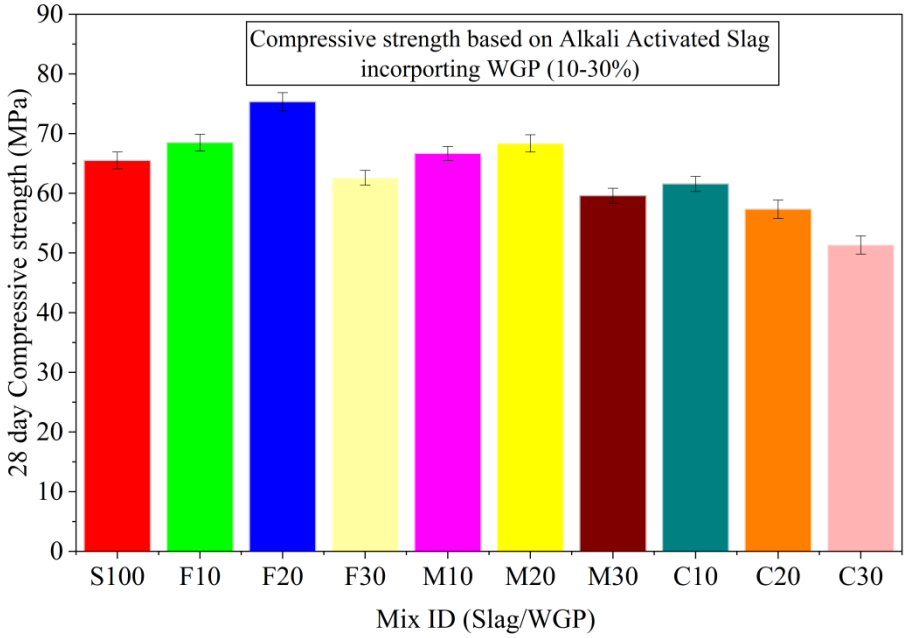


**Figure 3**. 28 days Compressive strength of Alkali activated slag based.

The medium particle-size mixes showed moderate performance. The M20 mix achieved 67.8 MPa, which was slightly higher than the control. This suggests that the 75–150 µm WGP size may still provide some filler effect and limited reactivity, but its performance is lower than the finer WGP. The coarse WGP mixes showed lower experimental compressive strength. The C30 mix had the lowest 28-day strength of

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49.8 MPa, which was 23.4% lower than the control. This may be because coarse WGP particles have lower surface area and dissolve slowly in alkaline solution. As a result, they may behave mainly as inert particles rather than active precursors.

In slag-based alkali-activated binders, waste glass powder usually helps compressive strength only when its particle size is fine enough to react or when its grading improves packing without cutting slag too much. Very coarse glass tends to behave like weak filler, while very high replacement can still reduce strength even with fine glass because the slag fraction drops.

For compressive strength, the main size effect is the balance between reactivity and filler/packing. In slag-based alkali-activated systems, glass powder reacts more slowly than slag, so its strength contribution is often delayed; Xiao et al. reported that GP had a lower reaction rate than slag and needed about 28 days to show its contribution, but replacing up to 50% of slag still did not significantly harm late-age strength, with final strengths around 33.1–33.5 MPa. This delayed behavior helps explain why particle size matters so much: finer glass has more surface area, dissolves faster in alkali, and is more likely to join gel formation, while coarse glass is more often only a filler [7]. Experimental indication from slag-glass geopolymers shows that smaller glass particles generally raise strength up to a practical optimum. A notable study by Zhang et al. found that in GGBS–waste-glass geopolymers, compressive strength increased as glass particle size decreased; the best result came from the finest tested glass, with mean diameter about 49.0 μm and D50 about 41.9 μm, while glass with D50 above 300 μm had low chemical reactivity and hardly reacted with the alkaline solution. The same study also showed that, under favorable curing, the slag-plus-glass blend could reach high strength, including 46.5 MPa at 28 days for the fine-glass mix cured initially at 80 °C[40]. This supports the view that, in slag-based systems, fine glass can move from mostly inert filler toward a real reactive precursor when the particles are small enough and curing is strong enough[1], [41], [42], [43]. At the same time, the literature shows that finer is not automatically better in every mix, because strength also depends on how much slag is removed and how the solid skeleton packs. Liu et al. found that adding waste glass reduced 28-day strength in alkali-activated mortars when it replaced part of the binder, and they linked much of the loss to the lower slag proportion; for NaOH-activated mixes, replacing fly ash, slag, or all binder with waste glass reduced compressive strength from 12.76 MPa to 10.82, 9.73, and 9.78 MPa, respectively, with the lowest strength in the mix with only 30% slag[37]. Macova et al. similarly summarized that increasing waste-glass content has often lowered mechanical properties, with reported causes including higher Si/Al ratio, changes in solid-to-liquid ratio, larger mean particle size, and microcracks, although they also noted that fine waste glass powders can participate in geopolymerization and increase strength[44]. So, for slag-based AAMs, particle size cannot be separated from replacement level: if glass is fine but slag dilution is too strong, strength can still fall. Also, Harrison et al. also summarized results from other alkali-activated and cementitious systems point in the same direction and help interpret the slag data. Harrison et al. found that finer waste-glass distributions had higher pozzolanic reactivity, while the sample with the most coarse particles had the lowest compressive strength; they also showed that dosage matters, with 5–10% replacement improving strength but 15–20% reducing it[45] .

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Marcin et al. also reported a non-monotonic size effect, where smaller particles gave only a very small positive effect, while bigger particles improved compressive strength in their material[46]. That result likely reflects system-specific packing and grading effects rather than a general rule that coarse glass is more reactive. More broadly, very fine powders below about 100 µm, and especially below about 40 µm, are often described as pozzolanic or highly active because they can react to form extra C-S-H–type products[47], [48]. The practical pattern is therefore a strength window rather than a single best size. Fine glass can raise or preserve strength by improving packing and later reaction, but only to a point. For example, Ziejewska et al. reported that glass up to 63 µm increased compressive strength at additions up to 20%, while 30% caused a drop below the reference; in the same study, a much coarser unsorted glass with mean size about 550 µm still gave large gains at 20–30%, showing again that grading and matrix compatibility can sometimes outweigh simple fineness rules[16]. Camargo et al. likewise found that, under constant processing conditions for sodium-silicate-activated blast-furnace slag, particle-size differences did not significantly change the extent of alkali activation, but they did affect packing, permeability, drying, and therefore compressive strength and reliability; a coarser and narrower size distribution favored mechanical reliability[39]. So the most defensible synthesis for slag-based alkali-activated materials is: strength usually improves as waste-glass powder becomes finer until the glass is reactive enough and packing is improved, but the benefit can level off or reverse if replacement is too high, if slag dilution dominates, or if the size distribution hurts the hardened pore structure[40], [43], [49], [50], [51], [52], [53], [54], [55], [56]. Recent studies outside pure slag replacement systems are consistent with this trend. Fine or very fine glass powders have been linked with strength gains at moderate replacement in geopolymer systems, such as 20% fine recycled glass in metakaolin-based mortar, or 25% WGP in a fly ash–GGBFS geopolymer reaching 68.61 MPa under ambient curing, but these are different chemistries from direct glass-for-slag substitution and should be used mainly as supporting context[57], [58]. Likewise, Mehta et al. studied several waste-glass powders with median sizes from about 4.65 to 21.26 µm in high-calcium fly-ash geopolymers, again reinforcing that very fine glass is now being used to target strength development, though not in a pure slag matrix[59].

**Effect of Particle Size and Replacement Level**

The results from Figures 2 and 3 indicate that the compressive strength of alkali-activated slag-based mortar does not depend only on whether WGP is added, but also on the balance between glass fineness, glass content, and slag replacement level. The best performance was obtained when fine WGP was used at a moderate replacement level, particularly in the F20 mix. This suggests that 20% fine WGP may provide an effective balance between maintaining enough reactive slag and introducing enough fine glass powder to improve packing and supply additional silica. When the replacement level increased to 30%, even fine WGP did not continue to improve strength. This indicates that the positive effect of WGP has a limit. At higher replacement levels, slag dilution becomes more influential. Since slag is the main source of calcium and reacts quickly under alkaline activation, reducing the slag content too much can weaken the binder system. In this case, the slower reaction of WGP

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cannot fully replace the rapid contribution of slag, particularly at early ages. The medium WGP mixes showed that some strength improvement is still possible when the glass size is not extremely fine, but the improvement is smaller. This is likely because the medium particles improve packing to some extent but do not dissolve as quickly as fine WGP. The coarse WGP mixes, especially C30, confirmed that large glass particles are not suitable when used at high replacement levels in slag-based alkali-activated mortar. Their low reactivity and weak contribution to gel formation appear to reduce the overall strength.

Recent studies also suggest that the relationship between particle size and strength is not always perfectly linear. Camargo et al. noted that particle-size distribution can affect packing, permeability, drying behaviour, and mechanical reliability in sodium-silicate-activated blast-furnace slag systems. This means that the best strength performance is not simply achieved by making all particles as fine as possible; rather, the particle size distribution must support both chemical reaction and dense packing. However, in the present results, the general trend is clear: fine WGP performed better than medium and coarse WGP, especially at the 20% replacement level[39].

**Overall Interpretation**

Overall, the compressive strength results show that the incorporation of WGP can improve the performance of alkali-activated slag-based mortar when used carefully. The F20 mix was the optimum mix at both 7 days and 28 days, achieving 54.0 MPa at 7 days and 72.0 MPa at 28 days. This indicates that 20% fine WGP replacement enhanced the mortar strength by improving particle packing and possibly contributing reactive silica during alkali activation. However, the results also show that increasing the WGP replacement level or using coarser WGP can reduce compressive strength. The reduction in F30 compared with F20 suggests that excessive replacement of slag can reduce early and later strength because of slag dilution. The poor performance of C30 confirms that coarse WGP particles are less reactive and may behave mainly as inert filler. Therefore, the use of WGP in alkali-activated slag mortar should be optimized rather than simply increased. Based on the 7-day and 28-day results, it can be concluded that fine WGP at 20% replacement is the most effective option for improving compressive strength in the studied alkali-activated slag-based mortar. The findings agree with the wider literature, which shows that fine glass powder can improve strength through filler effects and delayed chemical reaction, while high replacement levels and coarse glass particles may reduce strength because of low reactivity and reduced slag content.

**Mechanistic interpretation and practical particle-size/replacement guidance**

The main rule is simple: finer waste glass powder is more likely to react, while coarser glass is more likely to improve flow by lowering surface-area demand and changing packing. In slag-based alkali-activated materials, a practical target is usually fine-but-not-excessive glass at moderate replacement, because both particle size and slag dilution control the final result. Create waste glass powder as sitting on a spectrum from inert filler to reactive precursor. Coarse glass particles tend to react little and mainly change packing and fresh-state lubrication, while finer particles dissolve faster in alkali

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and can contribute to gel formation and later strength. This is why strength generally rises as glass becomes finer, at least until other limits such as slag dilution or poor grading take over[60]. For flow, larger particle size often helps because it lowers liquid demand. When GP is coarser than the material it replaces, it usually has lower specific surface area and needs less liquid for wetting, so more free liquid remains for flow. This explains why slag-based mixes often show a small slump-flow increase as GP content rises, and why GP can improve workability compared with much finer silica fume or metakaolin[2], [35]. For strength, the key size threshold is whether the glass is fine enough to become meaningfully reactive. Multiple sources point to sub-100 µm glass as a practical reactive range, with especially strong activity often reported below about 40 µm; by contrast, glass above about 300 µm can show very low reactivity in alkaline systems. In slag-glass geopolymers, the best reported strength in the cited size-comparison work came from glass with mean diameter about 49 µm and D50 about 41.9 µm[2], [7], [35], [46], [60]. Delayed reaction is normal, so particle size matters more at later ages than at early ages. GP reacts more slowly than slag, and about 28 days may be needed before its positive contribution is clear. In practice, this means coarse GP can look harmless or even helpful for fresh behavior but still add little to early strength, while fine GP has a better chance to support later-age hardening[7].

Replacement level should be chosen together with particle size, not separately. Even reactive fine glass can reduce strength if too much slag is removed. Across the broader literature, moderate dosage is repeatedly safer than high dosage: around 5–10% was optimal in one notable particle-size/dosage study, while 15–20% reduced strength; review-type sources also often describe about 10–20% as a practical range for strength or workability, with around 20% commonly workable[5], [45]. For slag-based AAMs specifically, about 20% replacement is a reasonable starting point, then adjust by fineness. This level often gives a useful workability gain and limits slag dilution. In alkali-activated slag, 20% GP increased slump flow by about 7%, and broader summaries also report workable mixes with GP replacing slag up to about 40%, but strength preservation depends on the glass being fine enough and the curing conditions being adequate[5], [7], [35]. A practical size/replacement guide for slag-based systems is: If GP is coarse (>300 µm): use mainly to tune flow or packing, not as a major reactive slag replacement; strength gains are unlikely from chemistry alone[7]. If GP is moderate-fine (~40–100 µm): this is often the most useful range for balancing workability, packing, and later reactivity in slag-based binders[16], [60]. If GP is very fine (<40 µm): reactivity can be high, but water demand, agglomeration risk, and mix sensitivity also rise, so replacement should usually stay moderate unless the whole binder design is optimized[5]. Do not use fineness alone as the design rule; size distribution also matters. A coarser but narrower grading can improve processing stability and mechanical reliability by changing packing, viscosity, permeability, and drying behavior, even when the overall extent of alkali activation changes little. This helps explain why some studies report benefits even with relatively coarse or unsorted glass: the whole grading curve and matrix compatibility can outweigh simple “finer is always better” thinking. Why coarse unsorted glass can still look good in some studies: It can densify the matrix or alter the granular skeleton in a favorable way, even if it is not highly reactive. For example, unsorted glass with mean size about 550 µm improved

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density, specific surface area, and compressive strength at 20–30% in one geopolymer study, while in the same report glass up to 63 µm improved strength only up to 20% and then dropped at 30%. The lesson is not that coarse glass is generally better, but that particle-size effects depend on how grading interacts with the rest of the mix[16].A simple design takeaway for the user's question: If the goal is better flow, use GP that is not too fine and keep replacement moderate. If the goal is maintained or improved compressive strength, use finer GP ideally in the reactive fine range and avoid replacing so much slag that dilution dominates. The best practical balance in slag-based alkali-activated materials is usually a moderate replacement with fine-to-moderate-fine GP, then tuning activator and curing around that choice.

**Mechanism of Gel Formation in Alkali-Activated Slag Mortar Containing High-Calcium Slag and High-Silica Waste Glass Powder**

In alkali-activated slag-based mortar, the gel formation mechanism mainly depends on the interaction between the high-calcium slag and the high-silica waste glass powder (WGP) in a highly alkaline environment. Slag is rich in CaO, $SiO_2$, and $Al_2O_3$, while waste glass powder is mainly rich in amorphous $SiO_2$. When both materials are activated using alkaline solutions such as sodium hydroxide, sodium silicate, or a combination of both, their glassy structures start to dissolve and release reactive ions into the pore solution. These ions then combine to form binding gels, mainly C-A-S-H, C-(N)-A-S-H, and, in some silica-rich regions, N-A-S-H gel.

**Dissolution of Slag and Waste Glass Powder**

The first stage is the dissolution stage. Under alkaline conditions, hydroxide ions attack the amorphous structure of slag and waste glass powder. Slag dissolves relatively quickly because it is highly reactive and calcium-rich. It releases $Ca^{2+}$, $SiO_4^{4-}$, and $AlO_4^{5-}$ species into the solution. Waste glass powder also dissolves, but usually more slowly than slag because it is mainly silica-based and has lower calcium and alumina contents.

The dissolution of slag can be simplified as:

$$\text{Slag} + OH^- + H2O \rightarrow Ca2+ + \text{Si species} + \text{Al species}$$

The dissolution of waste glass powder can be simplified as:

$$\text{Waste glass powder} + OH^- \rightarrow \text{dissolved silicate species}$$

Because waste glass powder contains a high amount of amorphous silica, it mainly supplies additional silicate species to the reaction system. This silica contribution is more effective when the glass particles are fine, because finer particles have a larger surface area and dissolve more easily in the alkaline solution. Previous studies have reported that glass powder reacts more slowly than slag, but it can contribute more clearly at later ages, especially around 28 days, when more silica has dissolved and participated in gel formation.

**Formation of C-A-S-H Gel from High-Calcium Slag**

The main reaction product in alkali-activated slag systems is usually calcium-aluminosilicate-hydrate gel, commonly written as C-A-S-H gel. This gel forms when calcium released from slag reacts with dissolved silicate and aluminate species. Since

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slag contains a high amount of calcium, it promotes the rapid formation of C-A-S-H gel, which is responsible for early strength development.
The general gel formation process can be explained as:
$Ca2++SiO44-+AlO45-+H2O \rightarrow$C-A-S-H gel
This C-A-S-H gel fills pores, binds particles together, and forms a dense matrix. It is the main reason why alkali-activated slag mortar can gain high compressive strength at early ages. In your results, this helps explain why the control slag-based mortar already achieved high strength, and why the mixes with suitable amounts of fine waste glass powder showed further improvement. The high-calcium slag provides the calcium needed for rapid gel formation, while fine WGP improves packing and supplies extra silica[6], [7].

**Role of High-Silica Waste Glass Powder**
The waste glass powder plays a slightly different role from slag. Since WGP is rich in silica but low in calcium, it does not form strong calcium-rich gels by itself unless enough calcium is available from slag. In a slag-WGP system, the slag supplies calcium, while the glass powder supplies additional silica. This extra silica can modify the gel structure by increasing the Si/Ca ratio of the binding gel as shown in

**Figure 4**.
At moderate replacement levels, this can be beneficial. The additional silica from fine WGP may help form a more polymerised and denser C-(N)-A-S-H gel. This type of gel is similar to C-A-S-H but contains some sodium within or near the gel structure because sodium ions are supplied by the alkaline activator. The presence of extra silica can make the gel network more connected, which may reduce porosity and improve compressive strength.

The simplified mechanism can be written as:

Ca from slag+Al from slag+Si from slag and WGP+Na from activator$\rightarrow$C-(N)-A-S-H gel

This mechanism explains why fine WGP at moderate dosage, such as the F20 mix in your results, produced the highest strength at both 7 and 28 days. The fine WGP likely acted in two ways: first as a filler that improved particle packing, and second as a reactive silica source that helped form additional or more silica-rich binding gel.

**Formation of N-A-S-H Gel in Silica-Rich Areas**
In areas where the system has more silica and sodium but less calcium, a secondary gel known as sodium-aluminosilicate-hydrate gel, or N-A-S-H gel, may also form. This gel is more common in low-calcium alkali-activated materials, such as fly ash or metakaolin systems. However, in slag-WGP systems, some N-A-S-H-type gel can form locally because waste glass powder increases the silica content of the matrix.

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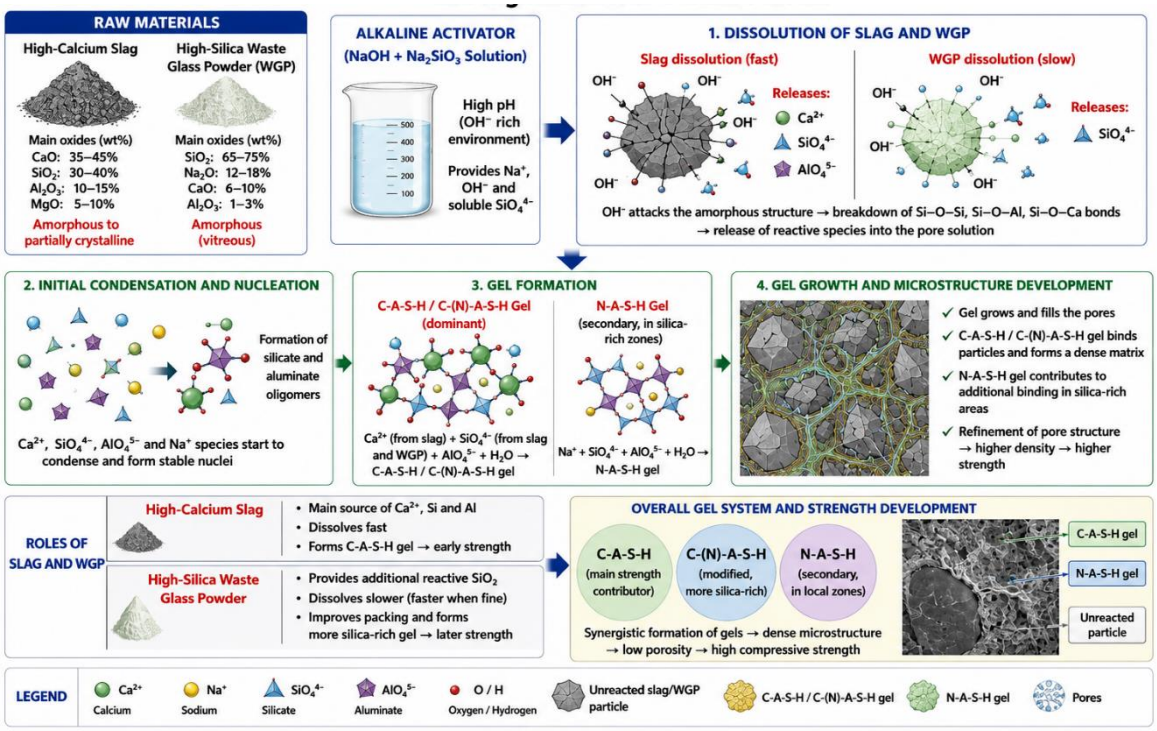


**Figure 4.** Gel formation of high calcium (Slag) and high silica (WGP) binders.

The formation of N-A-S-H gel can be expressed as:

$$Na^{+} + AlO_4^{5-} + SiO_4^{4-} + H_2O \rightarrow \text{N-A-S-H gel}$$

In high-calcium slag systems, C-A-S-H or C-(N)-A-S-H remains the dominant binding gel. However, the presence of WGP may encourage a mixed gel system where C-A-S-H, C-(N)-A-S-H, and some N-A-S-H coexist. Recent studies on alkali-activated slag systems have identified dense microstructures containing both C-A-S-H and N-A-S-H gel phases, especially when sodium silicate activators or silica-rich components are involved[61].

**Why Fine WGP Improves Gel Formation more than Coarse WGP**

The particle size of WGP is very important. Fine WGP dissolves faster because it has a larger surface area. This means more silica becomes available for reaction. When this dissolved silica reacts with calcium and alumina from slag, the gel becomes denser and stronger. This explains why the fine WGP mixes, especially F20, performed better in compressive strength.

Coarse WGP behaves differently. Because coarse particles have lower surface area, they dissolve slowly. Much of the coarse glass may remain unreacted inside the matrix. In that case, it behaves mainly as inert filler rather than an active precursor. If too much slag is replaced by coarse WGP, the system loses reactive calcium-rich slag, but the coarse glass does not provide enough reactive silica quickly enough. This leads to weaker gel formation and lower compressive strength. This agrees with your strength results, where the coarse WGP mixes showed lower strength, and C30 had the weakest 28-day performance. The lower strength is likely due to reduced slag content, limited glass dissolution, lower gel formation, and a less dense microstructure.

**Why Excessive WGP Replacement can Reduce Strength**

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Although WGP can improve gel formation at moderate replacement levels, too much WGP can reduce strength. This happens because slag is the main source of calcium. If a large amount of slag is replaced by WGP, the calcium content of the binder decreases. Without enough calcium, the formation of C-A-S-H gel becomes limited. This is important because C-A-S-H gel is the main strength-giving phase in alkali-activated slag mortar. High-silica WGP can supply silica, but it cannot fully replace the role of calcium-rich slag. Therefore, an optimum balance is needed. In your results, 20% fine WGP appeared to provide this balance. However, at 30% replacement, even fine WGP caused a reduction in strength compared with F20 because the slag dilution effect became stronger. Liu et al. also reported that replacing part of the binder with waste glass in alkali-activated slag-fly ash mortars could reduce compressive strength when the slag proportion became too low. This supports the idea that WGP is useful only when enough slag remains available to provide calcium for gel formation[62].

**Conclusion**

This study experimental the effect of WGP particle size on the flow and compressive strength of slag-based alkali-activated mortar. Based on the experimental results, the following conclusions can be drawn:

The flow of the mortar was strongly influenced by WGP particle size. Fine WGP reduced flow, while coarse WGP increased flow.

The lowest experimental flow was observed in the F30 mix, containing 30% WGP smaller than 75 µm. This was mainly due to the high surface area of fine glass powder.

The highest experimental flow was obtained by the C30 mix, containing 30% WGP in the 150–300 µm size range.

The highest experimental compressive strength was achieved by the F20 mix, containing 80% slag and 20% WGP below 75 µm.

At 28 days, F20 reached a experimental strength of 72.0 MPa, which was 10.8% higher than the 100% slag control.

Higher WGP replacement, especially at 30%, reduced strength because of slag dilution.

Coarse WGP improved flow but reduced compressive strength, suggesting that it behaved mainly as filler rather than as a reactive precursor.

Overall, 20% replacement of slag with WGP below 75 µm appears to be the optimum experimental mix for strength, while 20% WGP in the 75–150 µm range may offer a better balance between flow and strength.

5. Recommendations

The experimental results should be verified through laboratory testing using actual flow and compressive-strength experiments.

XRF testing should be conducted on the specific slag and waste glass powder used in the study, because oxide composition can vary depending on source.

The F20 mix, containing 80% slag and 20% WGP below 75 µm, should be prioritized for further testing because it showed the highest experimental strength.

Additional microstructural tests such as SEM, XRD, and FTIR are recommended to confirm whether fine WGP contributes to additional gel formation.

Future studies should examine durability properties such as water absorption, sorptivity, sulphate resistance, drying shrinkage, and alkali-silica reaction risk.

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The activator ratio may be further optimized, especially for fine WGP mixes, because reduced flow may affect casting and compaction quality.
For practical construction use, the final mix should balance strength, flowability, cost, activator demand, and waste-glass processing energy.

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