

Effect of Activated Carbon and Waste Glass Powder on the Compressive and Flexural Strength of Fly-Ash-Based Geopolymer Concrete

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Abstract: Portland cement (OPC) remains the default binder for concrete almost everywhere, yet its manufacture is one of the more carbon-intensive steps in the construction supply chain, and alkali-activated geopolymer binders are among the more mature alternatives on offer. Geopolymers are formed by activating an aluminosilicate precursor - fly ash, slag, metakaolin, and several natural pozzolans have all been used - with a strongly alkaline solution, and the resulting matrix can match or exceed OPC concrete on several counts, including early strength gain and resistance to elevated temperature. A large amount of that work has focused on fibers and on nano- or micro-silica as strength-enhancing additives; comparatively little has looked at two additives that are, in effect, waste streams in their own right: activated carbon and finely ground waste glass. We tested both, separately, as partial substitutes for the fly ash in an alkali-activated (NaOH plus sodium silicate) class-F fly-ash geopolymer concrete. Activated carbon replaced 1, 2, and 3 wt% of the fly ash; waste glass powder (400 mesh) replaced 5, 10, and 15 wt%. Cube and prism specimens were cast, cured at 90 °C for 24 h, and tested at 7 and 28 days for compressive strength (BS EN 12390-3) and flexural strength (ASTM C348). Both additives raised strength relative to the unmodified control across most of the ranges tested, though not monotonically: activated carbon peaked at 2% replacement, where 28-day compressive strength rose by roughly 8% and flexural strength by roughly 22%; waste glass powder peaked at 10%, with corresponding gains of about 18% and 29%. These optimum replacement levels are specific to the mixture design, materials, and curing regime investigated here and should not be assumed to generalize without further testing. In both series, the improvement was consistently larger for flexural than for compressive strength, which points toward a microstructural mechanism - pore-filling and interfacial densification - rather than a purely pozzolanic one, although the two are not mutually exclusive and are discussed together. Beyond the mechanical case, using two waste-derived materials as fly-ash substitutes is a reasonably direct way to divert them from landfill and reduce demand on virgin fly ash.

Keywords: Geopolymer concrete; Fly ash; Activated carbon; Waste glass powder; Compressive strength; Flexural strength; Alkali activation; Sustainable construction materials.

1. INTRODUCTION

Concrete is, by volume, the most widely used manufactured material on earth, and Portland cement (OPC) - its binding phase - is central to almost every part of the built environment [1]. That centrality comes at a cost: producing a ton of OPC clinker releases on the order of a ton of CO₂, largely from the calcination of limestone and the fuel burned to reach clinkering temperature [2]. Cement manufacturing is commonly cited as responsible for somewhere between 5% and 7% of global anthropogenic CO₂ emissions [3], a figure that is difficult to reduce quickly given how deeply OPC is embedded in construction practice and codes. Since CO₂ is the single largest contributor to anthropogenic warming, at roughly 65% of the total effect [4], and cement production sits within the same 5-7% range of global emissions cited above [5], the case for a lower-carbon binder is not really in dispute; the harder question is what should replace OPC, at what cost to performance, and how quickly it can be adopted without undermining structural reliability.

Geopolymer binders are one of the more developed answers to that question. The chemistry traces back to Davidovits, who introduced the concept at the first European Conference on Soft Mineralogy in Compiègne in 1978 [6] and coined the term poly(sialate) for the alkali-activated aluminosilicate networks that form when a suitable precursor reacts with a strong base - sialate being shorthand for silicon-oxo-aluminate [7,8]. Three structural variants of poly(sialate) are recognized, shown schematically in Fig. (1) [9].

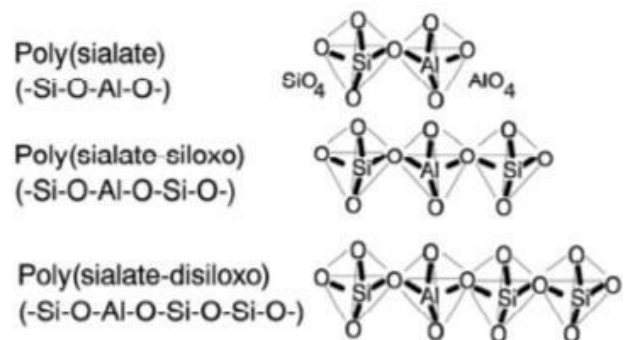


Figure 1: Chemical structure of poly(sialate) [9].

Geopolymers are, in short, inorganic polymers built from an amorphous aluminosilicate feedstock [10]. The

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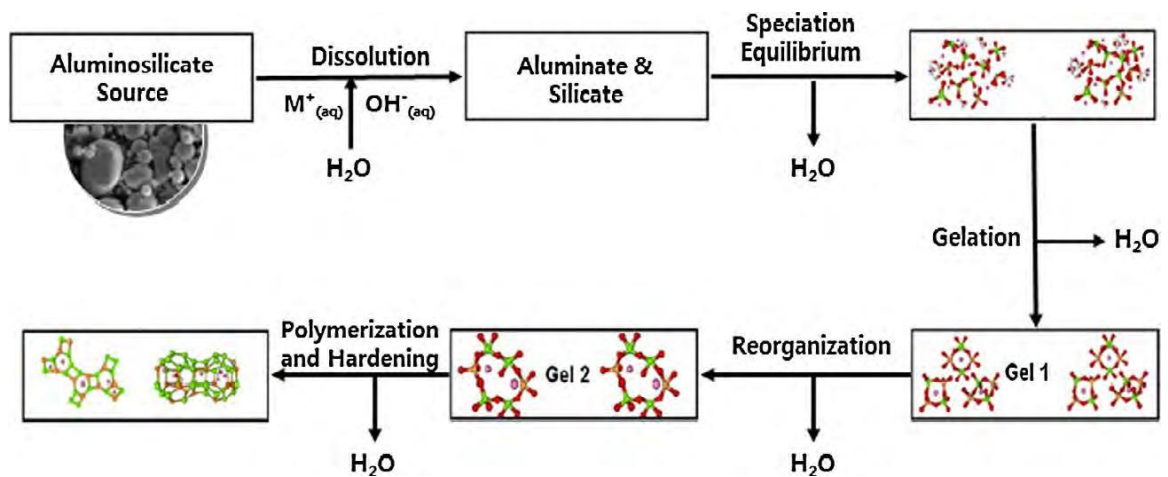


Figure 2: Schematic three-stage model of geopolymer formation [13].

resulting solid is often compared to zeolite, though the comparison only goes so far: zeolites are crystalline, geopolymers are not [11]. The reaction itself - between dissolved Si and Al species under alkaline conditions - proceeds quickly once it starts, and produces a disordered, three-dimensional Si-O-Al network [12]. That network forms across three overlapping stages. Dissolution comes first: the alkaline solution attacks the precursor's surface, breaking Si-O and Al-O bonds and releasing Si, Al, and O species into solution, with the rate governed by both the precursor's reactivity and the pH of the activator. Polymerization follows almost immediately, as the dissolved species recombine into poly(sialate) chains of varying length and composition. Hardening is the final stage, during which these chains lock into an amorphous solid; any crystalline phases that do appear form only in the period just before the mix sets, not afterward [13]. Fig. (2) sketches this sequence.

From a structural-engineering standpoint, none of this chemistry matters unless the resulting concrete performs at least as well as OPC concrete on the properties that govern design. On that front the record is fairly favorable: geopolymer concretes have repeatedly shown higher compressive and flexural strength than comparable OPC mixes [14-16], gain strength faster in the first days after casting [17], hold up better under fire and sustained high temperature [18-20], and resist chemical attack from acids and salts somewhat better as well [14,21], while remaining reasonably impermeable [14,22]. None of this requires an exotic or energy-intensive precursor - fly ash and ground granulated blast-furnace slag (GGBS) are both industrial by-products already produced at scale, and metakaolin is a comparatively simple calcined clay [14,21,22]. Picking the right precursor, and matching it to an activator solution formulated for that precursor's reactivity, is arguably the single most consequential

decision in a geopolymer mix design, since it sets the pace and extent of the dissolution step described above. Sodium hydroxide and potassium hydroxide are the two activators seen most often in the literature, usually paired with a sodium silicate solution [14]; that is the combination used here, activating a low-calcium class-F fly ash chosen for its favorable silica-to-alumina ratio and its long track record as a geopolymer precursor [23-25].

Whether any of this actually reduces the environmental footprint of concrete is, strictly, a separate question from whether it produces adequate strength, and it is usually addressed through life-cycle assessment (LCA) rather than through the mechanical testing that dominates the rest of this paper. In our own LCA of a slag-based geopolymer concrete, benchmarked against an OPC mix of comparable strength, the embodied-carbon reduction held up even after the energy cost of producing the alkaline activators was included [26] - a result broadly in line with the qualitative case made above. That finding, together with similar work from other groups, has fed into a wider discussion of where alkali-activated binders fit within green building practice, something we have written about directly [27], including a broader survey of the features that make geopolymer composites suited to green and sustainable urban construction [28], and that others have framed in terms of urban sustainability policy more broadly [29].

Fly ash is only one of several aluminosilicate feedstocks known to yield a workable geopolymer, and matching a precursor to whatever industrial by-product or natural mineral happens to be locally available is a recurring theme in this literature. We have worked through a fair amount of that space ourselves. Metakaolin turned out to be a useful contrast to fly ash: it is more reactive and dissolves faster, but that same

reactivity makes the mix more sensitive to activator concentration, and getting the mix design wrong shows up quickly as either flash-setting or poor strength development [30]. Ground granulated blast-furnace slag behaves differently again - it activates rapidly, including at ambient temperature without external curing, but its higher calcium content shortens working time and complicates casting of larger elements [31,32]. A class-C fly ash, which carries more CaO than the class-F material used in the present study, gave a useful point of comparison for how calcium content shifts the balance between geopolymerization and a more OPC-like hydration reaction [33]. At the more exploratory end, kaolinite, zeolite, and bentonite are all considerably less reactive on their own, but each has produced usable binders once combined with a more reactive co-precursor or a stronger activator [34-37]; a related line of work looked specifically at what happens when two or more alumina-silicate sources are deliberately blended in a single metakaolin-based mix, rather than used one at a time [38].

Strength development itself is not governed solely by the precursor - it also depends on how thoroughly the raw material is characterized and how the activator is formulated around it, and this is where a fair amount of our earlier work sits. Two studies looked specifically at what drives compressive-strength development in fly-ash- and metakaolin-based systems, respectively, and found broadly similar trends despite the different precursor chemistry: strength tracked activator molarity and curing temperature more closely than it tracked precursor fineness alone [30,39]. A separate, more synthesis-oriented paper worked through the geopolymer cement production route in more general terms, covering precursor selection, activator formulation, and curing together rather than treating them as independent variables [40]. On the activator side specifically, we compared several NaOH/sodium-silicate formulations across fly-ash and metakaolin precursors and, separately, tested activators built around class-C fly ash and around zeolite [33,35,41,42]; in every case the combined NaOH-and-sodium-silicate system outperformed either component used alone, which is why it was carried forward into the mix design used here.

Additives are a second, largely independent lever for improving geopolymer concrete, and the literature on them is dominated by two categories: fibers (polypropylene, polyolefin, and various hybrid combinations) and nano- or micro-scale silica [43]. A somewhat less conventional example - gelatin powder, almond shell, and recycled aggregate used together in an OPC concrete rather than a geopolymer one - illustrates how broadly "additive" gets defined in this

field, and how much of it is really about finding a use for a waste stream that would otherwise go to landfill [44]. Fiber reinforcement has been the more thoroughly studied route for geopolymer concrete specifically: hybrid polymer fibers improved both mechanical strength and high-temperature resistance in metakaolin-based mixes [45], polyolefin and simple fiber blends did something similar while also cutting water absorption [46], and slag-based mixes reinforced with hybrid fibers showed comparable gains [31,32]. A smaller, more targeted study combined two-element hybrid copolymer fibers with nano-silica particles in a metakaolin system and found the two additives interacted rather than simply adding their effects together [47]. Carbon-based and glass-based additives, by contrast, have received comparatively little dedicated attention in geopolymer concrete - which is the gap this paper is aimed at.

Activated carbon is a poor fit for the additive categories above, and it is worth being explicit about why. It is not carbon black, which is produced by partial combustion or thermal decomposition of hydrocarbons; activated carbon instead comes from pyrolyzing an organic precursor - wood residue and coal are both common feedstocks - in the absence of oxygen, which strips out the volatile fraction and leaves behind a highly porous carbon skeleton with a very large internal surface area. That porosity is what makes it useful as an adsorbent in water and gas treatment, and it is also what makes its behavior in a cementitious matrix hard to predict from first principles: a material with that much internal surface area could plausibly act as a physical filler, a partial pozzolan, or simply an inert diluent, and as far as we are aware, no prior study has tested which of these dominates in a geopolymer system.

Waste glass powder sits in a somewhat different position: it has been studied in OPC concrete, just not much in geopolymer concrete specifically. The motivation for looking at it at all is mostly environmental. Glass is chemically stable enough that it does not break down in a landfill on any timescale relevant to construction, and post-consumer glass that cannot be color-sorted or is otherwise unsuitable for remelting tends to end up there rather than back in the glass supply chain. At the same time, glass is largely silica, which gives it at least theoretical potential as a pozzolan or fine filler - a potential that the existing literature treats with some caution, since the reported effects of waste glass powder on OPC concrete are mixed rather than uniformly positive, depending heavily on particle size, replacement level, and the alkali-silica reaction (ASR) risk posed by the specific glass composition used [48-54].

Given how little of this has been tested specifically in a fly-ash geopolymer matrix, the aim of the present study is narrow and empirical: replace fly ash with activated carbon and, separately, with waste glass powder, across a small range of replacement ratios, and measure what happens to compressive and flexural strength at 7 and 28 days. To our knowledge, this is the first study to evaluate activated carbon and waste glass powder side by side, under the same fly-ash geopolymer mix design and curing regime, rather than examining either material in isolation or in an OPC matrix. The replacement ranges tested (1-3% for activated carbon, 5-15% for waste glass powder) were set on the basis of preliminary trial mixes, in which higher activated-carbon dosages produced a marked loss of workability and strength and higher waste-glass-powder dosages showed reduced performance consistent with the lower reactivity of glass-derived silica under the ambient curing conditions used; the resulting optimum replacement levels (2% and 10%, respectively) should accordingly be read as specific to this mix design rather than as general-purpose recommendations. The two additive series are treated independently rather than combined, since isolating each material's effect seemed more useful at this stage than testing a hybrid mix whose behavior would be harder to interpret. The results are reported in Section 3 and interpreted in Section 4, alongside a discussion of where they sit relative to our broader, ongoing work on the durability [55] and environmental performance [56-59] of geopolymer concrete as a construction material, including its use as an adsorbent in wastewater-treatment applications [60,61].

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Aluminosilicate Precursor

The aluminosilicate precursor used throughout this study was a low-calcium (class-F) fly ash of Indian origin. Its oxide composition, determined by X-ray fluorescence (XRF), is given in Table 1 and plotted in Fig. (4); a photograph of the as-received material appears in Fig. (3). The combined SiO_2 and Al_2O_3 content, at just over 90 wt%, is what makes this particular fly ash a reactive aluminosilicate source in the first place - most of the remaining mass is Fe_2O_3 , with the alkali and alkaline-earth oxides (CaO , MgO , K_2O ,

Na_2O) each present only in trace amounts, which is also why this material is classified as class-F rather than the more calcium-rich class-C.



Figure 3: Class-F fly ash used in this study.

Oxide composition of the class-F fly ash (XRF, wt%)

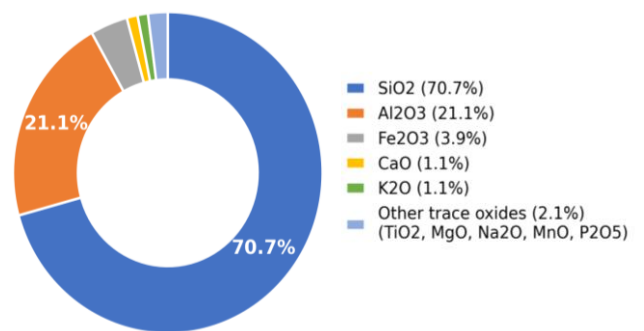


Figure 4: Oxide composition of the class-F fly ash used in this study, determined by X-ray fluorescence (see Table 1).

2.1.2. Activated Carbon and Waste Glass Powder

Waste glass powder, ground to 400 mesh, was sourced from glass-processing workshops around Tehran. Activated carbon powder was purchased from Ghatran Shimi (Tehran, Iran). Both materials are shown in Fig. (5).

2.1.3. Alkaline Activator

Sodium hydroxide (98% purity, Ghatran Shimi) and a liquid sodium silicate solution ($\text{SiO}_2:\text{Na}_2\text{O} = 2$, Isfahan Nafis Silicate Co.) together formed the alkaline activator. Their chemical analyses are given in Table 2 and 3, respectively.

Table 1: XRF Analysis of the Class-F Fly Ash Used in this Study (wt%)

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	TiO_2	Na_2O	MnO	P_2O_5
70.7	21.1	1.13	3.90	0.77	1.09	0.92	0.26	0.05	0.05

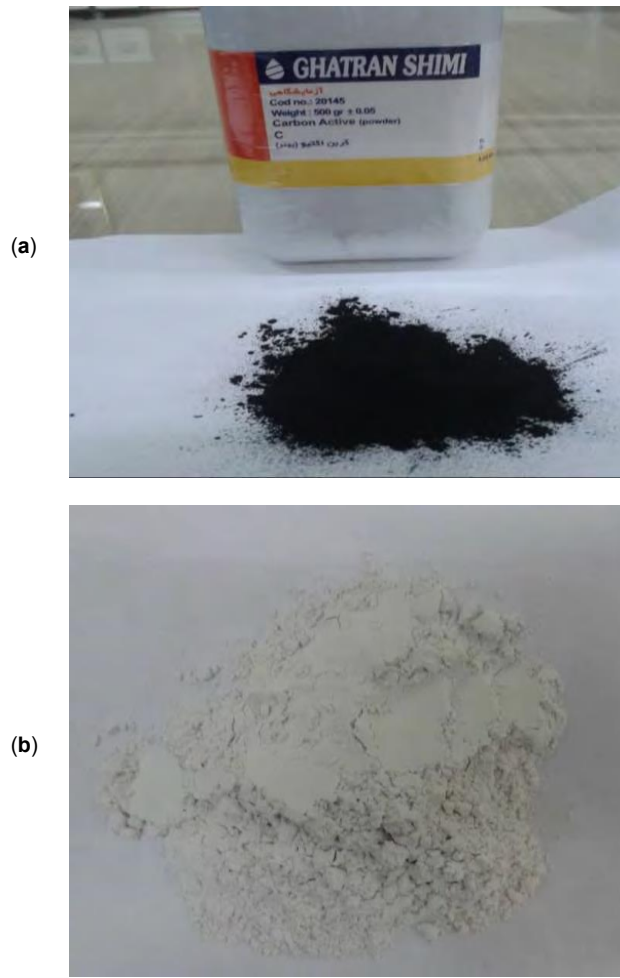


Figure 5: (a) Activated carbon and (b) waste glass powder used in this study.

Table 2: Chemical Analysis of the Sodium Hydroxide (NaOH) Used in this Study

Chemical Analysis	Result	Unit
NaOH	98	%
Na ₂ CO ₃	1	%
NaCl	200	ppm
Fe	6	ppm
SiO ₂	15.7	ppm
Appearance	White flake	-

Table 3: Chemical Analysis of the Sodium Silicate (Na₂SiO₃) Solution Used in this Study

Chemical Analysis	Result	Unit
SiO ₂	30.00	%
Na ₂ O	14.50	%
Water	55.50	%
Appearance	Clear liquid	-

2.1.4. Aggregates, Superplasticizer, and Water

Sand and gravel were obtained from quarries near Tehran, oven-dried, and separated into two size fractions (7 mm and 10 mm) following ASTM grading practice; the combined fine-aggregate fineness modulus was 3.103. Mixing water was ordinary Tehran municipal tap water. A polycarboxylate-based superplasticizer (Ghatran Shimi) was added to maintain workability across the additive series, since both activated carbon and finely ground glass tend to increase water demand relative to fly ash alone.

2.2. Mix Proportions

Two independent series of mixtures were prepared. In the first, activated carbon replaced 1%, 2%, and 3% of the fly ash by weight (Table 4). In the second, waste glass powder replaced 5%, 10%, and 15% of the fly ash by weight (Table 5). A single control mixture, denoted F and containing no additive, was shared as the baseline for both series.

The following ratios were held fixed across every mixture in both series:

- sodium silicate solution to NaOH solution, 1.5 by weight;
- superplasticizer, 2.5% of the control mixture's fly-ash weight, held constant across all mixtures in both series;
- sand to gravel, 1:1 by weight;
- gravel, graded 7-10 mm;
- fly ash (binder) to total aggregate, 23% by weight;

Table 4: Mix Proportions - Series 1 (Activated-Carbon [AC] Replacement of Fly Ash; SP = Superplasticizer)

Mixture	Fly Ash (kg/m ³)	Act. Carbon (kg/m ³)	NaOH (kg/m ³)	Na ₂ SiO ₃ (kg/m ³)	Gravel (kg/m ³)	Sand (kg/m ³)	SP (kg/m ³)	AC Replacement
F	400	0	80	120	840	840	10	0%
FC-1	396	4	80	120	840	840	10	1%
FC-2	392	8	80	120	840	840	10	2%
FC-3	388	12	80	120	840	840	10	3%

Table 5: Mix Proportions - Series 2 (Waste-Glass-Powder Replacement of Fly Ash; SP = Superplasticizer)

Mixture	Fly Ash (kg/m ³)	Glass Powder (kg/m ³)	NaOH (kg/m ³)	Na ₂ SiO ₃ (kg/m ³)	Gravel (kg/m ³)	Sand (kg/m ³)	SP (kg/m ³)	Glass Replacement
F	400	0	80	120	840	840	10	0%
FG-5	380	20	80	120	840	840	10	5%
FG-10	360	40	80	120	840	840	10	10%
FG-15	320	60	80	120	840	840	10	15%

- total aggregate to total concrete weight, approximately 73%.

The alkaline activator was prepared a day ahead of casting: NaOH flakes were dissolved in water to give a 12-molar solution, which was then combined with the sodium silicate solution and superplasticizer once cooled, and left for 24 h before use to allow the exothermic dissolution heat to dissipate. On casting day, the dry constituents - fly ash, the relevant additive (activated carbon or waste glass powder), sand, and gravel - were dry-mixed for 3 min before the activator solution was introduced, after which mixing continued for a further 3 min. Cube specimens measuring 100 × 100 × 100 mm for compressive testing and prism specimens measuring 40 × 40 × 160 mm for flexural testing were cast in the same batch, consolidated on a vibrating table for 10 s, and cured at 90 °C for 24 h before demolding; specimens were then stored under ambient laboratory conditions until the 7- and 28-day test ages. Three replicate specimens (*n* = 3) were tested per mixture and per test age, and the strength values reported in Section 3 represent the arithmetic mean of these three measurements; individual specimen-level values and a corresponding measure of variability were not retained in the records available for this study. Compressive strength was measured per BS EN 12390-3 (testing of hardened concrete – compressive strength of test specimens); flexural strength was measured per ASTM C348 (flexural strength of hydraulic-cement mortars), using center-point (three-point) loading.

Beyond the replacement ratio, the second series followed the same procedure as the first in every respect - same activator preparation, same mixing sequence, same curing regime, same test standards - so that differences in the results can be attributed to the additive itself rather than to a procedural change between series.

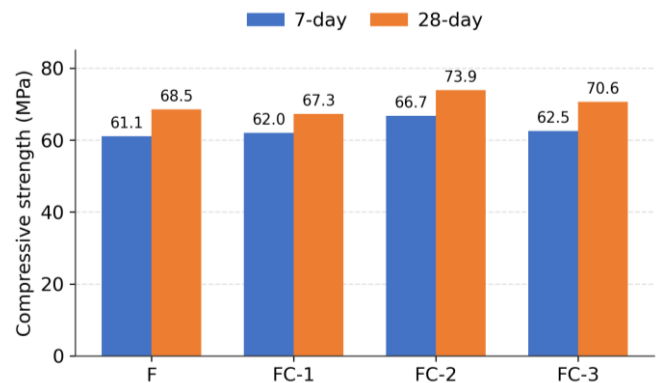
2.3. Nomenclature of Mixtures

F denotes the unmodified control mixture. FC-1, FC-2, and FC-3 denote 1%, 2%, and 3% fly-ash replacement by activated carbon; FG-5, FG-10, and FG-15 denote 5%, 10%, and 15% replacement by waste glass powder.

3. RESULTS

3.1. Effect of Activated Carbon on Compressive Strength

Fig. (6) summarizes the compressive-strength results for the activated-carbon series. The control mixture reached 61.1 MPa at 7 days and 68.5 MPa at 28 days. At 1% activated carbon (FC-1), 7-day strength rose slightly to 62.0 MPa (+1.5%), but 28-day strength fell marginally to 67.3 MPa (-1.8%) - the only case in either series where 28-day strength did not exceed the control. At 2% (FC-2), strength was highest in this series at both ages: 66.7 MPa at 7 days (+9.2%) and 73.9 MPa at 28 days (+7.9%). At 3% (FC-3), strength dropped back from the FC-2 peak - 62.5 MPa at 7 days and 70.6 MPa at 28 days (+2.3% and +3.1%, respectively) - while still remaining above the control at both ages.

**Figure 6:** Effect of activated-carbon replacement on the compressive strength of fly-ash-based geopolymers.

3.2. Effect of Activated Carbon on Flexural Strength

Flexural results for the same series are shown in Fig. (7). Unlike compressive strength, flexural strength increased at every replacement level and every age tested. The peak again occurred at 2% activated carbon: 7.1 MPa at 7 days (+20.3% over the 5.9 MPa control) and 8.3 MPa at 28 days (+22.1% over the 6.8 MPa control). FC-1 and FC-3 gave smaller but still positive gains - roughly +10% and +12% at 7 days, and +9% and +12% at 28 days, respectively - so the FC-2 mixture stands out as a fairly clear optimum within the range tested rather than one point on a flat trend.

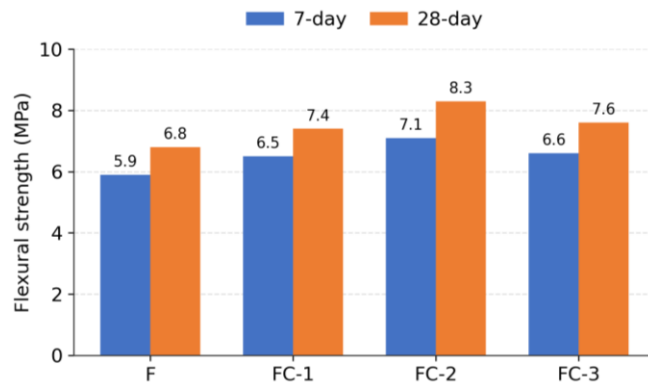


Figure 7: Effect of activated-carbon replacement on the flexural strength of fly-ash-based geopolymer concrete.

3.3. Effect of Waste Glass Powder on Compressive Strength

Fig. (8) gives the compressive-strength results for the waste-glass-powder series. Strength increased with replacement level up to 10% and then declined slightly: FG-5 reached 69.7 MPa (7 days) and 77.4 MPa (28 days); FG-10, the peak of this series, reached 72.2 MPa and 81.1 MPa; and FG-15 eased back to 71.6 MPa and 79.5 MPa. Relative to the control, 28-day compressive strength increased by roughly 13%, 18%, and 16% at 5%, 10%, and 15% glass replacement, respectively - gains noticeably larger, across the board, than anything achieved with activated carbon.

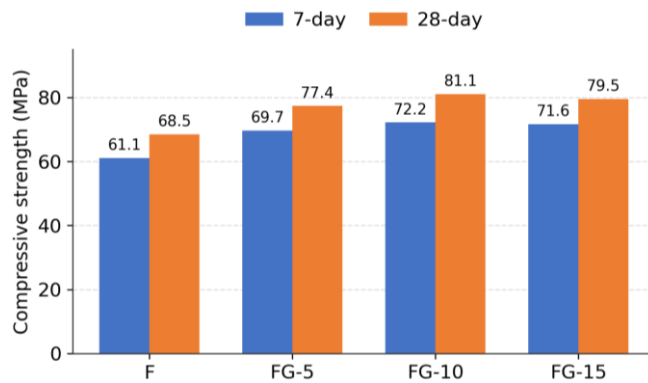


Figure 8: Effect of waste-glass-powder replacement on the compressive strength of fly-ash-based geopolymer concrete.

3.4. Effect of Waste Glass Powder on Flexural Strength

Flexural results (Fig. 9) followed the same pattern as compressive strength in this series, peaking at FG-10 with 7.6 MPa (7 days, +28.8%) and 8.8 MPa (28 days, +29.4%). FG-5 and FG-15 again fell short of that peak but still cleared the control by a wide margin - roughly +20% and +24% at 7 days, and +21% and +25% at 28 days, respectively.

Fig. (10) collects the 28-day percentage changes from both series on a single set of axes, which makes

two things easier to see at once: flexural strength responded more strongly than compressive strength to both additives, and waste glass powder outperformed activated carbon at every replacement level where a direct comparison is possible.

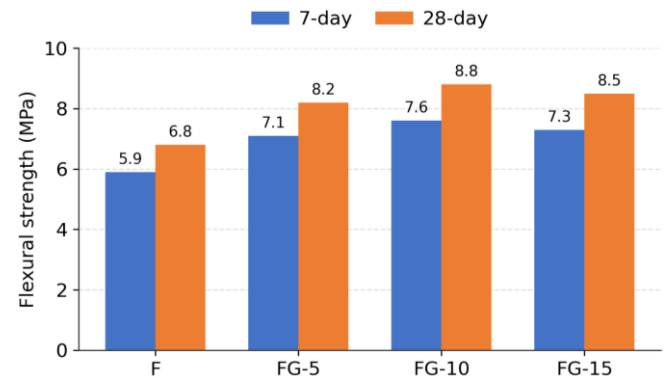


Figure 9: Effect of waste-glass-powder replacement on the flexural strength of fly-ash-based geopolymer concrete.

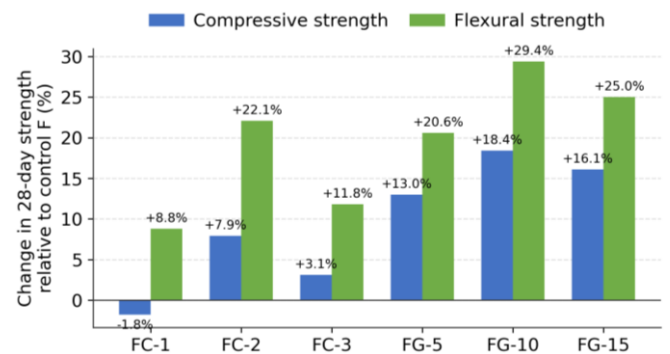


Figure 10: Percentage change in 28-day compressive and flexural strength relative to the control mixture (F), computed directly from the strength data in Figs. (6-9).

Plotting the same 28-day strengths as continuous trends against replacement ratio, rather than as discrete bars, makes the location of each series' peak harder to miss. Fig. (11) shows both properties rising and falling around 2% replacement for activated carbon and around 10% replacement for waste glass powder, with the compressive and flexural curves tracking each other closely enough that a single replacement level - not two different ones for the two properties - can reasonably be called optimal in each case.

4. DISCUSSION

4.1. Role of Activated Carbon in Strength Developme

Read together, Sections 3.1 and 3.2 point to a fairly narrow optimum for activated carbon: 2% replacement improved both compressive and flexural strength, while 1% and 3% gave weaker or, in one case (28-day compressive strength at 1%), slightly negative results. That non-monotonic pattern is easier to explain by two

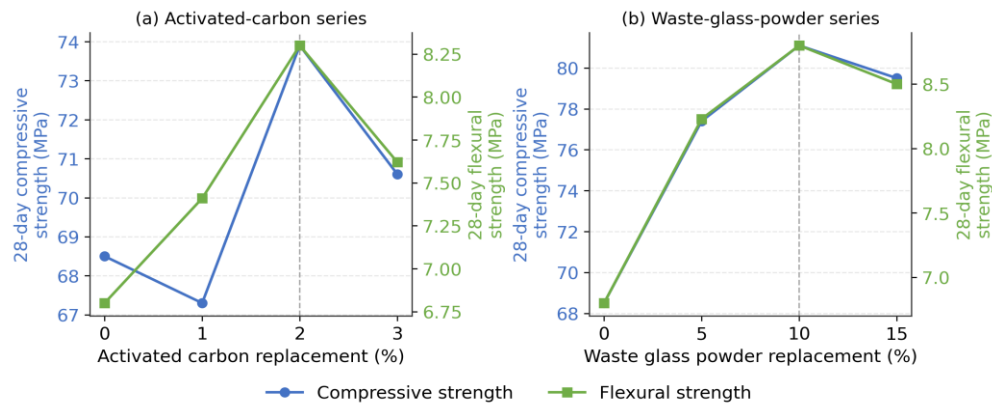


Figure 11: 28-day compressive and flexural strength plotted as continuous trends against replacement ratio for (a) the activated-carbon series and (b) the waste-glass-powder series, with the optimum replacement level in each series marked by a dashed line.

mechanisms working in opposite directions than by a single one. At low dosage, activated carbon's fine particles can fill capillary pores in the hardening matrix, and its very high surface area may allow it to participate, at least partially, in the aluminosilicate network as it forms - both effects consistent with the strength gains seen at 2%. Push the dosage higher, though, and the same porosity that makes activated carbon reactive also means it absorbs mixing water and alkaline solution, which can locally starve the geopolymerization reaction of the liquid it needs and leave behind a less continuous, more porous matrix - a plausible explanation for why FC-3 fell back from the FC-2 peak even though it still beat the control. The gap between activated carbon's effect on flexural strength (+22% at the optimum) and its effect on compressive strength (+8%) is also worth flagging on its own: it is a larger difference than would be expected from densification alone, and points toward some crack-bridging or crack-blunting behavior at the fine end of the pore network, which is difficult to confirm without microscopy. This

inference is the most plausible reading of the strength data available but has not been independently verified and should not be treated as a confirmed mechanism.

4.2. Role of Waste Glass Powder in Strength Development

Waste glass powder produced a cleaner result than activated carbon: strength rose monotonically from 5% to 10% replacement in both compressive and flexural terms, then eased back slightly at 15%, giving a single, unambiguous optimum at 10%. Two mechanisms plausibly explain the improvement, and neither excludes the other. The first is physical. The interfacial transition zone (ITZ) - the region immediately surrounding each aggregate particle, where the paste microstructure is more porous and more heavily microcracked than in the bulk paste - is widely recognized as a mechanically weak point in concrete, and fine, well-graded filler is one of the more reliable ways to densify it [62]. Fig. (12) sketches this pore-filling

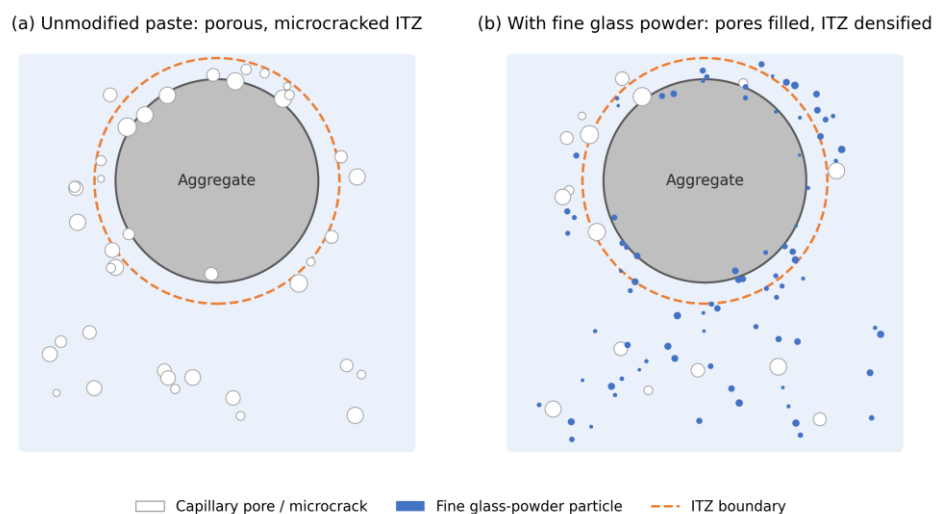


Figure 12: Schematic illustration of the proposed pore-filling mechanism at the aggregate interfacial transition zone (ITZ): (a) the unmodified paste, where the ITZ is relatively porous and microcracked, and (b) the same region after fine waste-glass-powder particles occupy capillary pores and densify the ITZ. Conceptual diagram, not drawn from microscopy data.

mechanism schematically: fine glass particles occupying capillary pores and lodging within the porous ITZ shell around the aggregate, next to a comparison of that filled microstructure with the coarser, more open pore structure of the unmodified paste. At 400 mesh, the glass powder used here is fine enough to plausibly play that role.

The second mechanism is chemical: waste glass is typically 70% or more SiO_2 by mass, with roughly 7-12% Na_2O [63-66], which puts it in the same broad compositional territory as a reactive pozzolan. Adding that much extra silica to the mix should push the system's Si/Al ratio toward the ~3.5 value commonly cited as favorable for geopolymer strength, and the accompanying sodium can, in principle, support further geopolymerization rather than simply diluting the binder. The direction of that effect, if not its magnitude, is consistent with what nano-silica additions do to ordinary Portland cement paste, where a comparable silica-driven densification of the matrix has been reported repeatedly, albeit at a particle size several orders of magnitude finer than the glass powder used here [67-69]. Distinguishing how much of the observed gain comes from each mechanism would require the kind of microstructural work - SEM, porosimetry - that falls outside the scope of the present study, but the falloff at 15% is at least consistent with the physical mechanism becoming self-limiting once the ITZ is adequately filled, after which further glass addition mainly displaces reactive fly ash without a compensating benefit. Both the physical (pore-filling) and chemical (pozzolanic) explanations should accordingly be read as plausible interpretations of the observed strength trends rather than confirmed mechanisms, in the absence of direct microstructural verification.

4.3. How these Results Sit Next to Related Work

Some comparison with prior findings, ours and others', helps put the size of these effects in context. The flexural gains reported here for waste glass powder (up to +29%) are larger than what fiber reinforcement typically delivers in geopolymer concrete - hybrid polymer fibers in a metakaolin system gave gains in the same broad range but required a much higher volumetric dosage and a more complicated mixing procedure to avoid balling [70]; polyolefin-fiber blends produced a smaller flexural gain alongside a useful reduction in water absorption that glass powder, on its own, would not be expected to replicate [46]. That is a useful reminder that "improves flexural strength" does not mean these additives are interchangeable with fibers - the mechanisms differ enough that the two approaches are probably complementary rather than competing. On the precursor side, the sensitivity we observed here to fine-particle dosage echoes what

turned up in earlier work on metakaolin- and fly-ash-based systems, where strength tracked activator concentration and curing conditions more tightly than precursor fineness on its own [30,39]; it would not be surprising if a similarly narrow dosage window applies to activated carbon and glass powder in slag- or metakaolin-based geopolymer concretes, though that would need to be tested directly rather than assumed from the fly-ash results reported here. The waste-glass literature in OPC concrete, by contrast, is considerably more equivocal than what we found - some studies report ASR-driven expansion and long-term strength loss at coarser particle sizes [51,53], which is at least part of why the 400-mesh grading used here was chosen deliberately rather than left to whatever glass happened to be available.

4.4. Where this Fits in the Broader Sustainability Case

Setting the mechanical results aside for a moment, there is a second argument for these two additives that has nothing to do with strength: both are, in effect, waste streams looking for a use. Activated carbon that has reached the end of its adsorptive life in water or air treatment, and glass that cannot be economically remelted, both currently end up disposed of rather than reused; routing even a modest fraction of either into geopolymer concrete as a fly-ash substitute reduces demand on virgin fly ash while giving each waste material somewhere useful to go - a related patent from our group covers a broadly similar valorization route for another waste stream, amorphous bagasse ash, used as a partial cement replacement [71]. That case is strongest when it is quantified rather than asserted, and our earlier LCA work on slag-based geopolymer concrete is the closest existing benchmark for what a full accounting might show [26] - though a proper LCA of the specific mixes tested here, accounting for the collection and processing energy of the two additives themselves, has not yet been done and would be needed before any firm claim about net environmental benefit could be made. The broader point, that geopolymer concrete's sustainability case depends on more than the precursor choice alone, is one we and others have made in review and policy-oriented work [27,29,72], and it applies just as much to secondary additives as it does to the primary binder.

4.5. Limitations and Future Work

The scope here is deliberately narrow, and the limitations follow from that: one fly ash source, one activator formulation, and two additives tested separately rather than in combination. The optimum replacement ratios identified - 2% for activated carbon, 10% for waste glass powder - should be read as specific

to this mix design rather than as general values; a different fly ash, a different activator molarity, or a different curing regime could plausibly shift them. A logical next step is to test the two additives together in a single mix, since their proposed mechanisms (pore-filling plus a possible pozzolanic contribution from the glass, versus a more porosity-driven effect from the carbon) are not obviously additive and could interact in either direction. Durability testing - water absorption, sulfate and acid resistance, freeze-thaw cycling, long-term shrinkage - was outside the scope of this study but would matter more than strength alone for most structural applications, and microstructural characterization (SEM/EDS, XRD, mercury intrusion porosimetry) would help confirm, or rule out, the mechanisms proposed in Sections 4.1 and 4.2 rather than leaving them as plausible inferences from strength data alone.

5. CONCLUSION

This study set out to measure, rather than assume, what happens to the compressive and flexural strength of fly-ash-based geopolymer concrete when part of the fly ash is replaced with activated carbon or with waste glass powder. Based on the testing described above:

- Activated carbon improved both compressive and flexural strength, but not monotonically with dosage; the optimum within the range tested was 2% replacement, giving roughly +8% compressive strength and +22% flexural strength at 28 days relative to the control mixture. This optimum is specific to the present fly ash, activator formulation, and curing regime, and should not be assumed to generalize to other mix designs.
- Waste glass powder improved both properties more strongly and more consistently than activated carbon did; the optimum was 10% replacement, giving roughly +18% compressive strength and +29% flexural strength at 28 days. As with activated carbon, this optimum is specific to the system investigated here rather than a general-purpose value.
- In both series, flexural strength responded more strongly than compressive strength, which is more consistent with a pore-filling and interfacial-densification mechanism than with a purely pozzolanic one, though the two mechanisms likely act together rather than separately.
- Because both additives are otherwise waste materials, using them as partial fly-ash substitutes offers a practical, if modest, way to reduce raw-material demand and divert waste

from landfill - a case that complements, rather than substitutes for, the broader environmental argument for geopolymer concrete over OPC concrete. This environmental case is presented as a motivating rationale rather than a demonstrated outcome, since a dedicated life-cycle assessment of these specific mixtures was not performed; quantifying the net environmental benefit is identified as necessary future work.

LIST OF ABBREVIATIONS

OPC	= Ordinary Portland Cement
GGBS	= Ground Granulated Blast-furnace Slag
LCA	= Life-Cycle Assessment
XRF	= X-ray Fluorescence
ITZ	= Interfacial Transition Zone
ASR	= Alkali-Silica Reaction
ASTM	= American Society for Testing and Materials
SEM	= Scanning Electron Microscopy
EDS	= Energy-Dispersive X-ray Spectroscopy
XRD	= X-ray Diffraction
F	= Control mixture (fly-ash-only geopolymer concrete)
FC	= Fly ash - Activated Carbon mixture series
FG	= Fly ash - Glass powder mixture series

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The datasets generated and analyzed during the present study are available from the corresponding author upon reasonable request.

AUTHORSHIP CONTRIBUTION STATEMENT

Alireza Esparham: Conceptualization, Methodology, Formal analysis, Investigation, Software, Writing – Original draft, Writing – Review & editing, Supervision, Project administration.

Alireza Nazarnezhad: Data curation, Validation, Resources, Writing – Review & editing.

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