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Effect of Recycled Fine Aggregates on the Performance of Slag-Fly Ash Blended Geopolymer Masonry Mortar

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Abstract **-** This paper aims to investigate the performance of slag-fly ash blended geopolymer masonry mortar (GMM) made with recycled fine aggregates (RFA). The effect of replacing natural fine aggregates (NFA) with RFA at 0 and 100% replacement rates was examined through three sets of GMM mixes comprising a binder-to-aggregates ratio of 1:2-1:3, a fly ash-to-slag ratio of 2:1-4:1, and a solution-to-binder ratio of 0.5-0.7. The precursor binder was activated using sodium silicate and sodium hydroxide at a mass ratio of 1.5. GMM mixes were evaluated for fresh and hardened properties. Test results showed that the flow was reduced by up to 12% upon 100% RFA replacement, with higher loss in mixes made with a higher fly ash-to-slag ratio. Meanwhile, RFA mixes had faster initial setting times than the control mix made with NFA, especially with a low binder-to-aggregates ratio of 1:3. For similar RFA replacement, the 28-day compressive strength decreased by up to 73%. The highest strength loss was noted for the mix made with a fly ash-to-slag ratio of 4:1. Yet, despite the deficit in performance due to RFA incorporation in GMM, all mixes complied with international standards for masonry applications. Such research findings provide evidence of the viability of utilizing RFA in cement-free masonry mortar, thereby contributing to enhancing the sustainability of the construction industry by conserving non-renewable natural resources and recycling wastes.

Keywords**:** masonry, mortar, geopolymer, recycled fine aggregates, sustainability.

1. Introduction

The substantial growth of civil engineering construction activities to meet the demands of the increasing population has led to a significant surge in greenhouse gas emissions and the depletion of non-renewable natural resources. In fact, the construction industry is accountable for 10% of CO_2 emissions, 20-50% consumption of natural resources, and 50% disposable of total solid waste material [1], [2]. In the year 2022, the United States reached its highest Portland cement production at 92 million tons, of which 2.5 million tons were dedicated to masonry cement production [3]. This significant consumption of cement leads to global warming and the occurrence of severe natural disastrous events [4]–[6]. In addition, 60-75% of the weight of standard concrete mixture is aggregates. As such, there is an excessive consumption of natural aggregates in the manufacturing of concrete and mortars [7], [8]. Due to the adverse environmental impact of concrete and its constituents, researchers, environmental activists, and governments are actively seeking environmentally friendly alternatives for both Portland cement and non-renewable natural aggregates.

Geopolymers are considered a viable alternative to Portland cement, not only reducing CO_2 emissions during production, but also providing superior mechanical and durability properties comparable to those of counterparts made with cement only. Many researchers reported enhanced performance of geopolymer mortars using different binders such as slag-fly ash [9], [10], volcanic ash [11], slag-calcinated lithomarge [12], and fly ash-palm oil fuel ash (POFA) [13]. Others investigated the effect of utilizing recycled fine aggregates (RFA) obtained from ceramic wastes [14]–[16], construction and demolition wastes [17], [18], and waste-based sands [19], [20] on the fresh and hardened properties of cement-based masonry mortar. Saba and Assaad [21] evaluated the suitability of metakaolin-based geopolymer mortar containing RFA. They noticed a strength enhancement upon incorporating 20% RFA, followed by a strength reduction at 40 and 60% replacement rates. Nevertheless, the performance of slag-fly ash blended geopolymer concrete masonry mortars made with 100% recycled fine aggregates has not yet been investigated.

This study aims to examine the influence of replacing natural fine aggregates (NFA) with RFA on the fresh and hardened properties of slag-fly ash blended geopolymer masonry mortar (GMM). The effect of different binder-to-aggregate ratio

(B:Agg), alkaline activator solution-to-binder (AAS:B) ratio, and fly ash-to-slag (FA:slag) ratio are also evaluated. The performance of GMM was characterized by the flow, setting time, and 28-day compressive strength.

2. Experimental Program

2.1. Materials

Class F fly ash (FA) and ground granulated blast furnace slag (referred to as slag) comprised the blended binder employed to develop the geopolymer mortar mixes. The composition of FA included 52.7%, 18.6%, 14.3%, and 8.3% of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO), respectively. On the other hand, slag consisted of 59.7%, 27.0%, and 7.5% of CaO, SiO_2, and Al_2O_3, respectively. NFA were natural crushed dolomitic limestone sand (CS) with a nominal maximum size (NMS) of 2.36 mm. Conversely, RFA were sourced from a recycling plant for construction and demolition waste (CDW) and graded to achieve a similar particle size distribution to NFA, as shown in Figure 1. Noteworthy that the gradation curve of NFA and RFA did not fall exactly within the limits recommended by ASTM C144 [22] but were not modified to reduce the energy footprint of GMM production. The specific gravity of FA, slag, NFA and RFA was determined as 2.32, 2.50, 2.69, and 2.63, respectively. Due to the higher absorption capacity of RFA, it was prewetted to achieve a saturated surface dry (SSD) state before being introduced into the mixture. AAS was prepared using a mixture of sodium hydroxide (SH) solution with a molarity of 8 M and grade N sodium silicate (SS) solution. Tap water was used for selected geopolymer mixes to enhance their flowability.

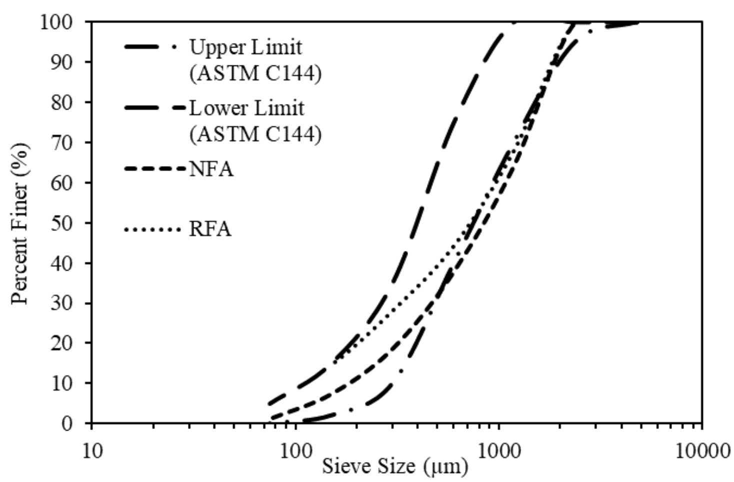

Figure 1: Particle size distribution of the fine aggregates.

2.2. Mixture Proportioning

Eight mortar mixes were prepared to examine the effect of B:Agg, FA:slag, and AAS:B ratios on GMM made with two types of aggregates, namely NFA and RFA. Table 1 presents the mixture proportions. Mixes were designated as W-X-Y-Z, where W denotes the type of aggregates (NFA or RFA), X illustrates the B:Agg ratio, Y indicates the FA:slag ratio, and Z is the AAS:B ratio. For instance, mix RFA-1:3-4:1-0.7 signifies a GMM made with RFA at a binder-to-aggregates ratio of 1:3, fly ash-to-slag ratio of 4:1, and AAS-to-binder ratio of 0.7. Five mixes were made with NFA, while the other three were produced with RFA. Mortar mixes were formulated using B:Agg ratio of either 1:2 or 1:3. The binder was a combination of slag and fly ash mixed at ratios of 2:1, 3:1, and 4:1. The use of such a blend eliminated the need for heat curing and mitigated shrinkage issues associated with fly ash-based geopolymer and alkali-activated slag geopolymer concrete, respectively [23], [24]. The AAS was comprised of sodium silicate and sodium hydroxide combined at a SS/SH ratio of 1.5, as recommended in previous work [25]. The AAS-to-binder ratio varied between 0.5-

0.7. Yet, a constant liquid-to-binder ratio of 0.7 was maintained across all mixes by adding tap water to achieve a minimal flow of 15.0 ± 0.2 cm.

Table 1: Mixture proportioning of slag-fly ash blended GMM mixes

Mix ID	Type of Aggregates	B:Agg	FA:Slag	AAS:B
NFA-1:3-4:1-0.50	NFA	1:3	4:1	0.50
NFA-1:3-4:1-0.60	NFA	1:3	4:1	0.60
NFA-1:3-3:1-0.65	NFA	1:3	3:1	0.65
NFA-1:3-2:1-0.70	NFA	1:3	2:1	0.70
NFA-1:2-2:1-0.70	NFA	1:2	2:1	0.70
RFA-1:3-4:1-0.70	RFA	1:3	4:1	0.70
RFA-1:3-3:1-0.70	RFA	1:3	3:1	0.70
RFA-1:2-2:1-0.70	RFA	1:2	2:1	0.70

2.3. Sample Preparation and Testing

The AAS was formulated by dissolving SH flakes in water to form an 8 M SH solution. Subsequently, SS was added at an SS/SH ratio of 1.5. The preparation of AAS took place a day before mixing, allowing for the dissipation of heat produced during the exothermic reactions when combining SH flakes with water and the SH solution with the SS solution. The casting process started with mixing the dry components, including binders and aggregates, for 2-3 minutes. Subsequently, AAS and additional water were introduced and mixed for another 2 minutes. The fresh mortar was cast in 50 mm cubic moulds, wrapped with plastic sheets for a day, and demoulded to be cured under ambient conditions until testing age.

The fresh properties of geopolymer mortar were evaluated using the flow and setting time by penetration resistance as per ASTM C1437 [26] and ASTM C403 [27], respectively. The hardened properties of geopolymer mortars were assessed using the 28-day compressive strength as per ASTM C109 [28]. Three specimens were tested for each mix, and an average value was calculated. Based on the average 28-day compressive strength, the geopolymer mortar was classified as Type N, S, or M in accordance with ASTM C91 [29].

3. Results and Discussion

3.1. Flow

Figure 2(a) presents the flow of GMM mixes. For NFA mixes made with FA:slag and AAS:B ratios of 2:1 and 0.7, respectively, decreasing the B:Agg ratio from 1:3 to 1:2 was accompanied with a 27% increase in the flow. This improved workability is primarily ascribed to the lower shear friction between the aggregates observed at higher binder contents [30]. On a similar note, increasing the AAS:B ratio from 0.5 to 0.6 in NFA mixes made with B:Agg and FA:slag ratios of 1:3 and 4:1, respectively, led to a slight increase in the workability, owing to the availability of excess solution to coat, separate, and reduce the friction between the particles [31]. Meanwhile, the flowability of GMM was not affected by the increase in the fly ash content. In fact, mixes made with FA:slag ratios of 3:1 and 4:1 exhibited flow values of 17.8 and 17.7 cm, respectively. In other work [32]–[35], higher flowability of geopolymer concrete was reported with higher fly ash contents due to the enhanced mobility of spherical-shaped fly ash and its slower reaction with AAS compared to the irregularly shaped slag particles. However, such an effect was notable only at elevated fly ash ratios and was not observed in the current study.

Utilizing RFA as a substitute for NFA led to a 12% reduction in the flow for mixes made with a B:Agg ratio of 1:3. This is mainly attributed to the higher specific surface area of RFA, as it reduces the binding paste needed to maintain workability. Similarly, Tiwari et al. [36] claimed that the enhanced flowability of mixes containing NFA is owed to the lower angularity and larger particle size of NFA compared to RFA, leading to lower interparticle friction and creation of thicker water layers in NFA mixes. In contrast, the inclusion of RFA into mixes with a higher binder content (B:Agg ratio of 1:2) had a negligible effect on the flow. Using a higher B:Agg ratio supplied excess water, thereby sustaining the workability of the RFA mix.

3.2. Setting Time

The initial and final setting times of GMM mixes are plotted in Figure 2(b). The initial setting time of the GMM varied between 21 and 52 minutes (min.), while the final setting time varied from 65 to 189 min. A decrease in the ratio in NFA mixes from 1:3 to 1:2 retarded the initial and final setting times from 39 to 50 min and from 70 to 92 min, respectively. This can be attributed to the sufficient amount of alkaline activator, facilitating the dissolution of the geopolymer binder and resulting in an increased level of geopolymerization [37]. Compared to the NFA-1:3-4:1-0.5 mix, increasing the AAS:B ratio to 0.6 led to 53 and 16% higher initial and final setting times, respectively. This finding is in agreement with that of other work [38] and is owed to the dilution of ions within the binder matrix, which obstructs the geopolymerization reaction [39]. Moreover, it was found that utilizing a higher FA:slag ratio of 4:1 instead of 3:1 resulted in an increase in the initial and final setting times (i.e., from 32 to 52 min and from 65 to 156 min, respectively). The results revealed that slag reacted rapidly with the alkaline activator in comparison to fly ash. This is primarily due to the higher calcium content existing in slag compared to fly ash, forming an amorphously structured calcium-aluminate-silicate hydrate (Ca-Al-Si-H) gel and accelerating the reactivity of the geopolymer binder [9], [33], [40].

The effect of substituting NFA with RFA on the setting time was also investigated. In comparison to NFA mixes made with a B:Agg ratio of 1:3, using 100% RFA shortened the initial setting time from 32 to 21 min. Although the final setting time appeared to be longer in RFA mixes than the NFA mixes, the former actually hardened earlier. In fact, cracks caused by subsequent penetrations during testing reduced the GMM resistance, leading to a larger apparent final setting time. Similarly, for mixes made with a B:Agg ratio of 1:2, utilizing RFA decreased the initial and final setting times from 50 to 27 min and from 92 to 65 min, correspondingly. This reduction in setting time is owed to the higher angularity and specific surface area of the RFA [41].

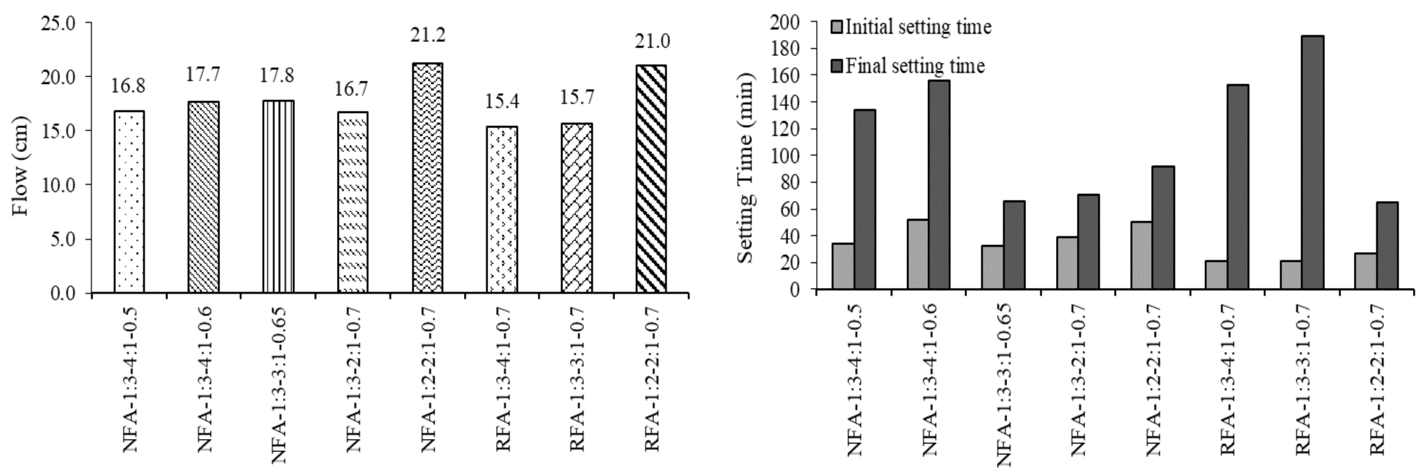

Figure 2: (a) Flow and (b) setting time of GMM mixes.

3.3. Compressive Strength

Figure 3 presents the 28-day compressive strength of geopolymer mortar mixes. For NFA mixes with FA:slag and AAS:B ratios of 2:1 and 0.7, respectively, decreasing the B:Agg ratio from 1:3 to 1:2 led to a 31% lower 28-day compressive strength. This reduction indicates that the optimum B:Agg ratio for strength development was 1:3. Beyond this ratio, the excess binder led to a highly workable mixture (with a flow of 21.2 cm) with more voids after hardening. Li et al. [42] reported a decline in compressive strength of fly ash-based geopolymer mortar, owing to the reduction in paste volume available for reaction. Increasing the AAS:B ratio of NFA mixes from 0.5 to 0.6 resulted in a 65% enhancement in the 28-day compressive strength. Likewise, Gugulothu and Rao [43] observed an initial rise in strength of geopolymer concrete with an increase in AAS content, followed by a decrease in strength with additional solution. Moreover, the influence of using different FA:slag ratios on the compressive strength of geopolymer mortar was also evaluated. Results revealed a 16% decline in the 28-day compressive strength upon increasing FA:slag ratio from 3:1 to 4:1 4:1 in the NFA mixes. This strength reduction is due to the lower calcium content with less slag being incorporated into the the mix, which, in turn, delays the polymerization reaction and hinders the formation of an amorphously structured Ca-Al-Al-Si gel [33].

Incorporating RFA in GMM mixes resulted in substantial strength reduction. Compared to NFA-1:3-4:1-0.6 and NFA-1:3-3:1-0.65 mixes, replacing 100% NFA with RFA decreased the compressive strength by 73 and 64%, respectively. Similarly, full substitution of NFA with RFA in mixes made with a B:Agg ratio of 1:2 decreased the strength by nearly 50%. The lower strength of RFA mixes is mainly attributed to the lower density and specific gravity of RFA. Furthermore, the presence of old cement mortar within recycled aggregates renders them weaker compared to natural aggregates [44]. Long et al. [45] related such strength reduction to the weaker bonding in the interfacial transition zone (ITZ) between the cement matrix and the surface of recycled aggregates.

Masonry mortars are categorized into N, S, and M types depending on their respective mean 28-day compressive strengths of 6.2, 14.5, and 20.0 MPa, as specified in ASTM C91 [29]. As displayed in Figure 3, NFA geopolymer mortar mixes generally fall under the M type, except for NFA-1:3-4:1-0.5, which exhibited the lowest strength and was consequently classified as an N-type mortar. On the other hand, RFA mixes demonstrated lower compressive strengths, placing mixes with a B:Agg ratio of 1:3 in the N type category, and that with a B:Agg ratio of 1:2 in the S type category. Such loss in performance is primarily owed to the weaker properties of the RFA compared to NFA and to the higher solution content in RFA mixes, which is needed to maintain flowability.

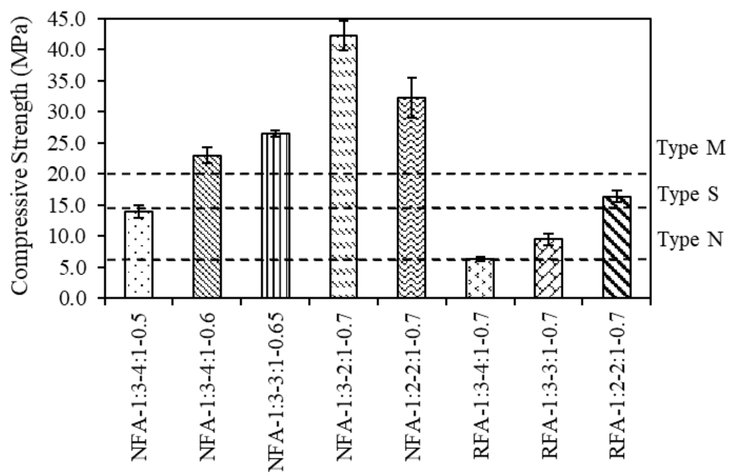

Figure 3: Compressive strength of GMM mixes.

4. Conclusions

The fresh and hardened properties of slag-fly ash blended GMM utilizing two types of aggregates, i.e., NFA and RFA, were evaluated. Different binder-to-aggregate, solution-to-binder, and fly ash-to-slag ratios were employed. Based on the experimental results, the following conclusions can be drawn:

- The flow of NFA mixes increased with higher binder and AAS contents. Conversely, a drop of 12% in the workability was observed when replacing NFA with RFA, with a higher loss in mixes made with a higher fly ash-to-slag ratio.
- The initial setting time of NFA mixes was delayed by 30, 53, and 60% with the increase in B:Agg, AAS:B, and FA:slag ratios, respectively. Meanwhile, RFA replacement led to 47 and 29% faster initial and final setting times, respectively.

- Increasing the AAS:B ratio from 0.5 to 0.6 improved the 28-day compressive strength by 65%. Conversely, a strength reduction was depicted at higher binder and fly ash ratios. The replacement of NFA with RFA decreased the compressive strength in NFA mixes made with B:Agg ratios of 1:3 and 1:2. Despite the performance decline in RFA mixes, they were classified as type N and S, as per the ASTM C91, rendering them suitable for various masonry applications.

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References

[1] M. M. Khasreen, P. F. G. Banfill, and G. F. Menzies, "Life-Cycle Assessment and the Environmental Impact of Buildings: A Review," *Sustainability*, vol. 1, no. 3, Art. no. 3, Sep. 2009, doi: 10.3390/su1030674.

[2] K. Ahmed Ali, M. I. Ahmad, and Y. Yusup, "Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector," *Sustainability*, vol. 12, no. 18, Art. no. 18, Jan. 2020, doi: 10.3390/su12187427.

[3] National Minerals Information Center, "Cement Statistics and Information," U.S. Geological Survey. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf

[4] S. Govindhan and V. Nivedha, "Experimental Study of Geopolymer Concrete Blocks," vol. 06, no. 03, 2019.

[5] N. B. Singh and B. Middendorf, "Geopolymers as an alternative to Portland cement: An overview," *Constr. Build. Mater.*, vol. 237, p. 117455, Mar. 2020, doi: 10.1016/j.conbuildmat.2019.117455.

[6] Z. Yas and K. Jaafer, "Factors influencing the spread of green building projects in the UAE," *J. Build. Eng.*, vol. 27, p. 100894, Jan. 2020, doi: 10.1016/j.jobe.2019.100894.

[7] Y. H. Labaran, V. S. Mathur, S. U. Muhammad, and A. A. Musa, "Carbon footprint management: A review of construction industry," *Clean. Eng. Technol.*, vol. 9, p. 100531, Aug. 2022, doi: 10.1016/j.clet.2022.100531.

[8] L.-Y. Shen, W.-S. Lu, H. Yao, and D.-H. Wu, "A computer-based scoring method for measuring the environmental performance of construction activities," *Autom. Constr.*, vol. 14, no. 3, pp. 297–309, Jun. 2005, doi: 10.1016/j.autcon.2004.08.017.

[9] J. Shang, J.-G. Dai, T.-J. Zhao, S.-Y. Guo, P. Zhang, and B. Mu, "Alternation of traditional cement mortars using fly ash-based geopolymer mortars modified by slag," *J. Clean. Prod.*, vol. 203, pp. 746–756, Dec. 2018, doi: 10.1016/j.jclepro.2018.08.255.

[10] S. V. Maruti, R. Krishna, and M. Mounesh, "Properties of Geopolymer Cement Mortar and Blocks with Calcium Carbonate," *Mater. Today Proc.*, vol. 24, pp. 1518–1524, 2020, doi: 10.1016/j.matpr.2020.04.471.

[11] J. N. Yankwa Djobo, A. Elimbi, H. Kouamo Tchakouté, and S. Kumar, "Mechanical properties and durability of volcanic ash based geopolymer mortars," *Constr. Build. Mater.*, vol. 124, pp. 606–614, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.07.141.

[12] J. Kwasny, M. N. Soutsos, J. A. McIntosh, and D. J. Cleland, "Comparison of the effect of mix proportion parameters on behaviour of geopolymer and Portland cement mortars," *Constr. Build. Mater.*, vol. 187, pp. 635–651, Oct. 2018, doi: 10.1016/j.conbuildmat.2018.07.165.

[13] N. Ranjbar, M. Mehrali, A. Behnia, U. J. Alengaram, and M. Z. Jumaat, "Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar," *Mater. Des.*, vol. 59, pp. 532–539, Jul. 2014, doi: 10.1016/j.matdes.2014.03.037.

[14] I. Martínez, M. Etxeberria, E. Pavón, and N. Díaz, "A comparative analysis of the properties of recycled and natural aggregate in masonry mortars," *Constr. Build. Mater.*, vol. 49, pp. 384–392, Dec. 2013, doi: 10.1016/j.conbuildmat.2013.08.049.

[15] J. R. Jiménez, J. Ayuso, M. López, J. M. Fernández, and J. De Brito, "Use of fine recycled aggregates from ceramic waste in masonry mortar manufacturing," *Constr. Build. Mater.*, vol. 40, pp. 679–690, Mar. 2013, doi: 10.1016/j.conbuildmat.2012.11.036.

[16] J. Silva, J. De Brito, and R. Veiga, "Recycled Red-Clay Ceramic Construction and Demolition Waste for Mortars Production," *J. Mater. Civ. Eng.*, vol. 22, no. 3, pp. 236–244, Mar. 2010, doi: 10.1061/(ASCE)0899-1561(2010)22:3(236).
[17] R. S. Mora-Ortiz *et al.*, "Effect of Pre-Wetting Recycled Mortar Aggregate on the Mechanical Properties of Masonry Mortar," *Materials*, vol. 14, no. 6, p. 1547, Mar. 2021, doi: 10.3390/ma14061547.
[18] A. De Rossi, M. J. Ribeiro, J. A. Labrincha, R. M. Novais, D. Hotza, and R. F. P. M. Moreira, "Effect of the particle size range of construction and demolition waste on the fresh and hardened-state properties of fly ash-based geopolymer mortars with total replacement of sand," *Process Saf. Environ. Prot.*, vol. 129, pp. 130–137, Sep. 2019, doi: 10.1016/j.psep.2019.06.026.
[19] A. Gholampour, V. D. Ho, and T. Ozbakkaloglu, "Ambient-cured geopolymer mortars prepared with waste-based sands: Mechanical and durability-related properties and microstructure," *Compos. Part B Eng.*, vol. 160, pp. 519–534, Mar. 2019, doi: 10.1016/j.compositesb.2018.12.057.
[20] P. Deng and Z. Zheng, "Mechanical properties of one-part geopolymer masonry mortar using alkali-fused lead–zinc tailings," *Constr. Build. Mater.*, vol. 369, p. 130522, Mar. 2023, doi: 10.1016/j.conbuildmat.2023.130522.
[21] M. Saba and J. J. Assaad, "Effect of recycled fine aggregates on performance of geopolymer masonry mortars," *Constr. Build. Mater.*, vol. 279, p. 122461, Apr. 2021, doi: 10.1016/j.conbuildmat.2021.122461.
[22] ASTM, "Standard Specification for Aggregate for Masonry Mortar," ASTM International, West Conshohocken, PA, Standard C144, 2018. doi: 10.1520/C0144-18.
[23] N. Ismail and H. El-Hassan, "Development and Characterization of Fly Ash–Slag Blended Geopolymer Mortar and Lightweight Concrete," *J. Mater. Civ. Eng.*, vol. 30, no. 4, p. 04018029, Apr. 2018, doi: 10.1061/(ASCE)MT.1943-5533.0002209.
[24] H. El-Hassan and N. Ismail, "Effect of process parameters on the performance of fly ash/GGBS blended geopolymer composites," *J. Sustain. Cem.-Based Mater.*, vol. 7, no. 2, pp. 122–140, Mar. 2018, doi: 10.1080/21650373.2017.1411296.
[25] J. Hwalla, H. El-Hassan, J. J. Assaad, T. ElMaaddawy, and J. Bawab, "Effect of Type of Sand on the Flowability and Compressive Strength of Slag-Fly Ash Blended Geopolymer Mortar," presented at the The 8th International Conference on Civil, Structural and Transportation Engineering, Canada, Jun. 2023. doi: 10.11159/iccste23.115.
[26] ASTM, "Standard Test Method for Flow of Hydraulic Cement Mortar," ASTM International, West Conshohocken, PA, Standard C1437, 2020.
[27] ASTM, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance," ASTM International, West Conshohocken, PA, Standard C403, 2016.
[28] ASTM, "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)," ASTM International, West Conshohocken, PA, Standard C109, 2021.
[29] ASTM, "Standard Specification for Masonry Cement," ASTM International, West Conshohocken, PA, Standard C91, 2023.
[30] S. Kumar, C. Sekhar Das, J. Lao, Y. Alrefaei, and J.-G. Dai, "Effect of sand content on bond performance of engineered geopolymer composites (EGC) repair material," *Constr. Build. Mater.*, vol. 328, p. 127080, Apr. 2022, doi: 10.1016/j.conbuildmat.2022.127080.
[31] Y. Ghasemi, M. Emborg, and A. Cwirzen, "Effect of water film thickness on the flow in conventional mortars and concrete," *Mater. Struct.*, vol. 52, no. 3, p. 62, Jun. 2019, doi: 10.1617/s11527-019-1362-9.
[32] P. S. Deb, P. Nath, and P. K. Sarker, "The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature," *Mater. Des. 1980-2015*, vol. 62, pp. 32–39, Oct. 2014, doi: 10.1016/j.matdes.2014.05.001.
[33] M. N. S. Hadi, N. A. Farhan, and M. N. Sheikh, "Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method," *Constr. Build. Mater.*, vol. 140, pp. 424–431, Jun. 2017, doi: 10.1016/j.conbuildmat.2017.02.131.

[34] H. Zhao, W. Sun, X. Wu, and B. Gao, “The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures,” *J. Clean. Prod.*, vol. 95, pp. 66–74, May 2015, doi: 10.1016/j.jclepro.2015.02.050.
[35] P. Nath and P. K. Sarker, “Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition,” *Constr. Build. Mater.*, vol. 66, pp. 163–171, Sep. 2014, doi: 10.1016/j.conbuildmat.2014.05.080.
[36] A. Tiwari, S. Singh, and R. Nagar, “Feasibility assessment for partial replacement of fine aggregate to attain cleaner production perspective in concrete: A review,” *J. Clean. Prod.*, vol. 135, pp. 490–507, Nov. 2016, doi: 10.1016/j.jclepro.2016.06.130.
[37] Y. Wang, Y. Wang, and M. Zhang, “Effect of sand content on engineering properties of fly ash-slag based strain hardening geopolymer composites,” *J. Build. Eng.*, vol. 34, p. 101951, Feb. 2021, doi: 10.1016/j.jobe.2020.101951.
[38] J. Hwalla, H. El-Hassan, J. J. Assaad, and T. El-Maaddawy, “Performance of cementitious and slag-fly ash blended geopolymer screed composites: A comparative study,” *Case Stud. Constr. Mater.*, vol. 18, p. e02037, Jul. 2023, doi: 10.1016/j.cscm.2023.e02037.
[39] C. Ruiz-Santaquiteria, J. Skibsted, A. Fernández-Jiménez, and A. Palomo, “Alkaline solution/binder ratio as a determining factor in the alkaline activation of aluminosilicates,” *Cem. Concr. Res.*, vol. 42, no. 9, pp. 1242–1251, Sep. 2012, doi: 10.1016/j.cemconres.2012.05.019.
[40] I. Garcia-Lodeiro, A. Palomo, and A. Fernández-Jiménez, “2 - An overview of the chemistry of alkali-activated cement-based binders,” in *Handbook of Alkali-Activated Cements, Mortars and Concretes*, F. Pacheco-Torgal, J. A. Labrincha, C. Leonelli, A. Palomo, and P. Chindaprasirt, Eds., Oxford: Woodhead Publishing, 2015, pp. 19–47. doi: 10.1533/9781782422884.1.19.
[41] A. Wongsa, A. Siriwattanakarn, P. Nuaklong, V. Sata, P. Sukontasukkul, and P. Chindaprasirt, “Use of recycled aggregates in pressed fly ash geopolymer concrete,” *Environ. Prog. Sustain. Energy*, vol. 39, no. 2, p. e13327, 2020, doi: 10.1002/ep.13327.
[42] H. Li *et al.*, “Effect of Fine Aggregate Particle Characteristics on Mechanical Properties of Fly Ash-Based Geopolymer Mortar,” *Minerals*, vol. 11, no. 8, Art. no. 8, Aug. 2021, doi: 10.3390/min11080897.
[43] V. Gugulothu and T. D. Gunneswara Rao, “Effect of Binder Content and Solution/Binder Ratio on Alkali-Activated Slag Concrete Activated with Neutral Grade Water Glass,” *Arab. J. Sci. Eng.*, vol. 45, no. 10, pp. 8187–8197, Oct. 2020, doi: 10.1007/s13369-020-04666-5.
[44] S. C. Kou and C. S. Poon, “Enhancing the durability properties of concrete prepared with coarse recycled aggregate,” *Constr. Build. Mater.*, vol. 35, pp. 69–76, Oct. 2012, doi: 10.1016/j.conbuildmat.2012.02.032.
[45] W.-J. Long, D. Zheng, H. Duan, N. Han, and F. Xing, “Performance enhancement and environmental impact of cement composites containing graphene oxide with recycled fine aggregates,” *J. Clean. Prod.*, vol. 194, pp. 193–202, Sep. 2018, doi: 10.1016/j.jclepro.2018.05.108.