Slag and Silica Fume-Based Geopolymer Mortar Using Locally Available Waste Filler Materials

Md. Nasimuzzaman, M. S. Ayon, and G. M. Sadiqul Islam

1 Introduction

Public attitudes toward conserving natural resources and reducing environmental degradation have led people to focus on habitual construction material substitutes in recent years. The current cement consumption is four billion tons/year, increasing by 4% every year. At this moment, ordinary Portland cement is the worlds' top binding material for concrete [1]. Portland cement manufacturing annihilates energy; notably, the process releases at least 0.7 ton of CO_2 into the atmosphere from one-ton cement production. In addition, various greenhouse gases, including nitrogen oxides and sulfur oxides, are being released [2]. Industrial wastes, including fly ash, ground granulated blast furnace slag (GGBS), mine waste, and red mud, have become a matter of concern as it requires land to fill and requires careful management. The urgency to explore practically usable alternative and eco-friendly substitutes to standard cementitious concrete has paved the way to develop new materials for the construction sector.

Geopolymer is an eco-friendly alternative to the traditional OPC-based concrete that can decrease 8% of greenhouse gas. In addition, industrial waste materials could be reused in its production [3]. The mineral binder is made by amalgamating aluminosilicate materials with a highly concentrated alkali solution. The dissolved alumina and silica species go through polymerization to form a three-dimensional amorphous structure providing comparable strength to the OPC-based concrete [4]. Better compressive strength and fire resistance, lower thermal conductivity, shrinkage and setting times, rapid hardening, excellent durability, and acid resistance have made geopolymer materials a better choice than ordinary Portland cement [5, 6]. The

Md. Nasimuzzaman (✉) · M. S. Ayon · G. M. S. Islam
Department of Civil Engineering, Chittagong University of Engineering & Technology, Chattogram 4349, Bangladesh

G. M. S. Islam
e-mail: gmsislam@cuet.ac.bd

S. Arthur et al. (eds.), *Advances in Civil Engineering*, Lecture Notes in Civil Engineering 184, https://doi.org/10.1007/978-981-16-5547-0_17

alkaline activator solutions comprise sodium or potassium-based soluble alkalis. It is often used to originate geopolymer concrete in the fusion of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [7]. The study indicated NaOH significantly impacts the structure and the compressive strength of geopolymers while used a concentration of 2–16 M [8]. The strength of mixes increased with NaOH concentration. However, flowability and setting time reduced. The polymerization reaction generally occurs at elevated temperatures or ambient temperatures [9]. For producing high-strength geopolymers, commonly, 12 M of NaOH solution is used, maintaining a low liquid-to-binder ratio of about 0.4 and curing temperature around 70 °C for at least 24 h. The binders mixed react more efficiently when the sodium-silicate-to-sodium-hydroxide mass ratio is between 2.0 and 2.5 [10]. Before testing compressive strength, all the specimens were cured in an oven for 18 h at 65 °C and placed at room temperature (about 26–29 °C) [11]. Geopolymers are connected to the group of strong and durable cementitious materials that harden at less than 100 °C [5, 12].

GGBS is a by-product of the steel industry. Its both pozzolanic and cementitious properties suggest this as a mineral admixture in concrete production. High-strength concrete can be produced from an alkali-activated GGBS binder. For every ton of steel, about half a ton of blast furnace slag is expected to be produced. Disposing of the slag as waste would have a negative impact on the environment. The early strength gain of GGBS in geopolymer concrete can reduce the construction cost and its disposal difficulties. Silica fume is a by-product generated from silicon-based elemental silicon or alloys in electric arc furnaces. This is an artificial, ultrafine, and amorphous glassy solid containing silicon dioxide spheres with high surface area and water demand [13]. Both GGBS and silica fume could be used as a binder in geopolymer mortar. Sand is an essential component in concrete construction and is generally used as filler. Natural sand is becoming a scarce commodity in the recent past. Natural sand extraction affects the amount of soil moisture that causes groundwater depletion to have an enormous and constant environmental influence [14]. Excavation of sand provokes the collapse of adjacent lands and causes to execute fluctuation of ecology [15]. To secure the remaining sand and gravel, unsheathing is excessively taxed or else prohibited in the various zone of the world [16]. Hence, the construction industries need to discover replacements to meet the propagated requirements for fine aggregates. Waste materials like brick dust, fly ash, and waste glass could replace sand. Using these waste materials as a filler replacement can be reduced environmental pollution, and it is also an alternative solution to the disposal challenge of these industrial wastes. This research, therefore, studied the performance of filler replacement by industrial wastes in GGBS and silica fume based geopolymers to conserve the environment and explore eco-friendly option for concrete filler.

2 Materials and Methods

2.1 Materials

Waste materials including GGBS and silica fume were used as a binder in geopolymer mortar. Brick dust, waste glass, fly ash, and EN sand are used to replace fine aggregate. NaOH (6 M) and sodium silicate were used as an alkali activator solution. GGBS was obtained from a cement industry sourced earlier from Japan. The material is off-white color mainly composed of calcium oxide, silica, and alumina (around 90%). The specific gravity of GGBS was found to be 2.56. Silica fume was obtained from Elkem production supplied by Consol Limited, Bangladesh. The particle size of silica fume ranges from 0.1 to 0.3 μm which is spherically shaped. It is a highly reactive pozzolana that contains silicon dioxide (around 90%). Specific gravity was found to be 2.48.

Fly ash was obtained from a Barapukuria Thermal Power plant in Bangladesh. The material is enriched with silica and alumina. Brick dust was obtained from a construction site of CUET. Also, the red color of the material may provide an attractive visual appearance. The waste glass was collected from a hotel in front of CUET. Waste glass is enriched with silica and calcium. EN standard [17] sand is natural sand imported from France. It is free from impurity and circular. It has isometric particles and generally is well graded.

Coarse-grained fine aggregate was obtained from the northeast region of Bangladesh. The gradation was matched with EN standard [17] requirements to compare performance between them. The particle size distribution of sand is given in Table 1. The maximum particle size of all filler materials is shown in Table 2.

Table 1 Particle size distributions of sand

Sieve No.	Sieve opening (mm)	% pass
8	2.36	100
16	1.19	75
30	0.6	25
50	0.3	18
Pan	–	0

Table 2 Maximum particle size of filler materials

Sample name	Passing through ASTM sieve	Max. particle size, mm
Standard sand	#100	2.36
EN Standard sand	–	2.00
Waste glass	#30	25
Brick dust	#50	18
Fly ash	#200	0.075

Initially, the required quantity of sodium hydroxide (NaOH) was placed in the beaker to prepare a 6 M solution. Next, a calculated amount of water was added and prepared for the suspension. Sodium silicate (Na_2SiO_3) was then mixed with the prepared 6 M NaOH suspension. The mixture of NaOH and Na_2SiO_3 solutions was prepared for not more than one hour before mixing the mortar for polymerization. In the alkaline solution, Na_2SiO_3/NaOH ratio was 2.5.

2.2 Sample Preparation

GGBS (80%) and silica fume (20%) were used as binders throughout the study. Fine aggregate in the mixture was partially (5–20%) replaced by waste glass, fly ash, brick dust, and EN standard sand. The detailed mix proportion is given in Table 3. In all these geopolymer mortars, a sand/binder ratio of 2.75 and an activator/binder ratio of 0.45 were used. The amount of excess water was determined from the flow test. A flow value of 185 ± 5 mm was taken as control water content. For uniformity, 22.5% (of binder content) excess water was added with the mixture to make the mortar workable.

Mix proportion of mortar (kg/m^3)

Table 3 Proportions of fine aggregates (sand and industrial waste) in geopolymer mortar

Mix	Sand	Brick dust	Fly ash	Waste glass	EN sand
Control	100	–	–	–	–
B5	95	5	–	–	–
B10	90	10	–	–	–
B15	85	15	–	–	–
B20	80	20	–	–	–
F5	95	–	5	–	–
F10	90	–	10	–	–
F15	85	–	15	–	–
F20	80	–	20	–	–
G5	95	–	–	5	–
G10	90	–	–	10	–
G15	85	–	–	15	–
G20	80	–	–	20	–
E5	95	–	–	–	5
E10	90	–	–	–	10
E15	85	–	–	–	15
E20	80	–	–	–	20

Mix ID	Fine aggregate		Binder		Alkaline solution		Water
	Natural sand	Industrial by-products	GGBS	Silica fume	NaOH	Na_2SiO_3	
Control	1365	0	400	100	64	160	112
B5	1300	70					
B10	1230	135					
B15	1160	205					
B20	1095	275					

2.3 Mixing and Curing

An automatic machine was used to mix the mortar as per EN 196-1 [18]. At first, graded sand was poured into a sand container. Next, sand replacement (5, 10, 15, and 20%) material (brick dust, fly ash, waste glass, and EN sand) was placed on top of the graded sand. Full binders are then placed inside the mixing bowl, and after that, a previously prepared and measured quantity of activator solution with the required water was poured one by one. Once the mortar mixing machine started, it mixes the binder and liquid first and then automatically intake the inert part and mixes it at a low speed. After an interval, the machine started automatically at high speed. Mixing was done at standard room temperature within a total of 4 min [18]. After finishing the mixing process, mortars were placed and compacted into a 40 × 40 × 160 mm rectangular mold as instructed in the standard [18]. Then the mortar was compacted using a jolting machine for 2 min. The samples were then kept at room temperature for 24 h. These were then demolded and kept in an oven at 60^0C for 18 h. After that, the samples were again placed at room temperature for the remaining period before testing at 3 and 7 days.

2.4 Compressive Strength Test

Compressive strength was tested at the age of 3 and 7 days as per BDS EN 196-1 [17]. The reported result was the average of six samples. The compression testing machine had a loading rate of 2400 ± 200 N/s. A standard jig had placed between the compression machine's platters to transmit the load to the compression surfaces of the mortar prism specimen. The test was carried out on halves of the prism broken by using suitable means which do not subject the halves to significant stresses. Each prism half was tested by loading its side faces using the compression testing machine. The compressive strength σ was calculated in MPa by dividing the maximum load at fracture (N) by 1600 (the area of the platens 40 mm × 40 mm) in square millimeters.

3 Result and Discussion

3.1 Workability

The variation in workability (measured through flow test) of mortars was evaluated by partially replacing various filler material. An additional water/binder ratio of 0.225 was maintained for preparing these mortar samples. A typical flow test is shown in Fig. 1. Different combinations of partially replaced filler materials gave mixed results. Control flow value (185 ± 5) mm without filler replacement was taken as standard. As shown in Fig. 2, the flow value varied depending on the replacement material type. A sudden increase in flow value was observed while the waste glass replaced 10% filler; this was similar for 15% replacement. At 20% replacement level, flow value decreased from the previous replacement level. Waste glass is composed of mainly silica, a relatively cleaner type of filler, therefore increasing the workability of

Fig. 1 **a** Mortar sample in brass mold and **b** Sample shape turned into a pancake shape

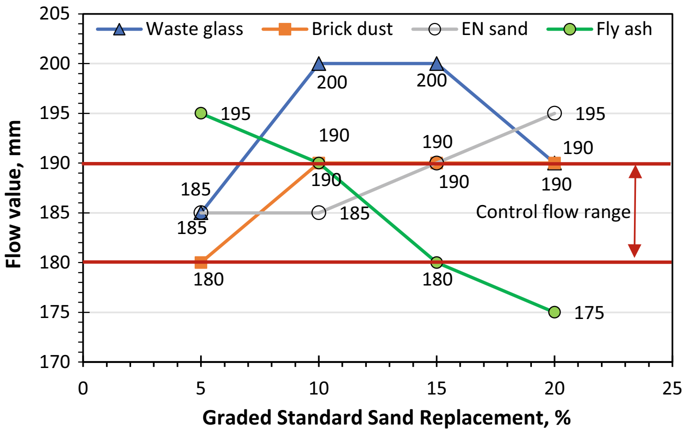

Fig. 2 Geopolymer mortar flow value

mortar. The study [19] found an increase in flow value by partially replacing cement with ground glass powder up to 25%. The waste glass used in this study was passed through the #30 (600 μm) ASTM sieve, which is smaller than the original filler (sand) that was replaced. Therefore, it gave a higher flow up to 15% replacement for being a relatively cleaner material. However, it is a smaller particle size than the original sand; its flow performance was slightly downgraded at a 20% replacement level in geopolymer mortars.

The brick dust was smaller than waste glass passing through #50 (300 μm) ASTM sieve. Change in flow value with brick dust was not significant. A 5% replacement gave lower flow, and all other replacement level gave a slightly higher value than control flow constantly. However, all the flow value with filler replacement by brick dust was within the range of control flow. The effect of impurities in filler sand used in Bangladesh was noted by replacing this with EN standard sand. Both of these materials were similar in particle size. The flow value was increased from control flow by replacing more local sand with EN standard cleaner sand. This is expected to improve significantly if a higher amount of EN sand is used. The use of fly ash as filler gave the opposite trend in flow value than other materials.

An increase in fly ash replacement level gave gradually decreased the flow value of mortar. With 15 and 20%, replacement gave a lower flow than the control flow. A study [20] with cement replaced by fly ash in concrete showed an increase in workability. This study worked with geopolymer mortars where the amount of water was limited to wet the constituent material. The finer segment of fly ash was obtained by passing them through the #200 (75 μm) ASTM standard sieve. Therefore, the surface area of the materials was much higher than the original filler sand. Thus, the available water could not thoroughly wet the enormous surface area of the finer fly ash, and the expected ball/bearing effect [21] of finer fly ash could not be started. Therefore, it is not recommended to replace more than 15% graded sand with fine fly ash in geopolymer mortars.

3.2 Compressive Strength

The compressive strength of geopolymer mortar was evaluated by replacing the filler material using a different possible alternative. The 3- and 7-days compressive strengths of geopolymer mortar are given in Table 4 and graphically represented in Figs. 3, 4, 5, and 6. The maximum compressive strength of geopolymer mortars was obtained with a 15% replacement of filler with brick dust. Sample B15 gave more than 200% compressive strength (at three days 45.8 MPa and seven days 46.6 MPa) than control strength of 3 days and 7 days (Fig. 3). A study [22] found significant improvement in the compressive strength of mortars by replacing cement with similar size brick dust with water-reducing admixtures. The performance of fly ash as filler replacement was not that impressive. No significant change in compressive strength was noted with the sand replacement by fly ash. Fly ash is expected to participate in

Table 4 Development of compressive strength (MPa) at different ages

Label	Control	B5	B10	B15	B20	F5	F10	F15	F20
3-day	19.6	16.4	37.8	45.8	44	15.7	13.9	14.5	15.4
7-day	21.5	17.8	44	46.6	44.7	16.3	16.2	15.3	15.5
Label	**E5**	**E10**	**E15**	**E20**	**G5**	**G10**	**G15**	**G20**	
3-day	17.5	14.6	18.4	39.6	9.9	14.7	20.4	19.9	
7 day	29.6	26.5	30	41.6	10.3	17.3	20.6	25.8	

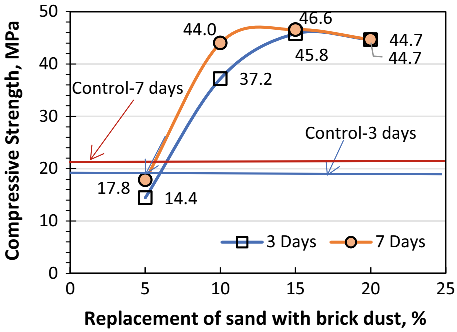

Fig. 3 Compressive strength of brick dust mortar

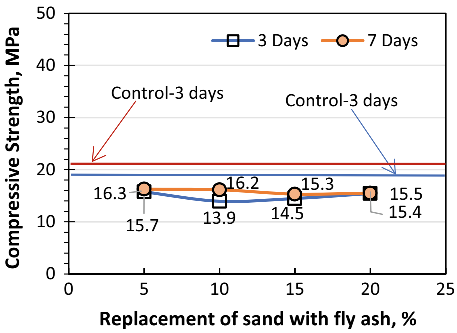

Fig. 4 Compressive strength of fly ash mortar

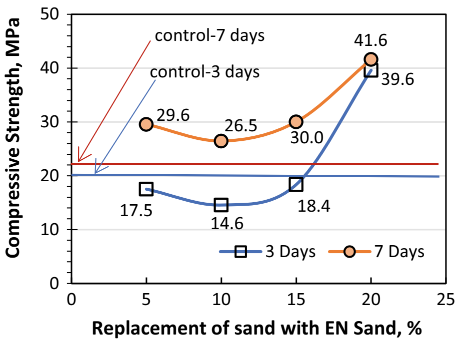

Fig. 5 Compressive strength of EN sand mortar

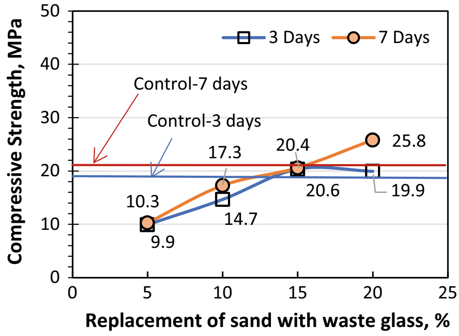

Fig. 6 Compressive strength of waste glass mortar

geopolymerization [23]; however, the compressive strength interfered by the workability (shown in Fig. 2). The compressive strength improvement of Portland–fly ash cement paste with silica fume was found higher than the blends without silica fume (for the same fly ash content) [20]. At both 3 days and 7 days, all fly ash mortar gave less strength than the control mixture (Fig. 4).

EN sand also gave a gradual improvement of geopolymer mortar compressive strength. The improvement mainly was noted for 7 days of curing (Fig. 5). In both three and 7-days curing, 20% replacement gave maximum compressive strength (Fig. 5). The improvement of strength with 20% sand replacement (sample E20) by EN standard sand was around 200%, reflecting the effect of possible impurities present in filler materials. Although the grading of locally obtained sand and EN standard sand was similar, the EN sand gave a better fresh performance of geopolymer mortars which was also reflected in its compressive strength results. A gradual increase in compressive strength was found by replacing the graded sand with waste glass powder (Fig. 6). With 15% (G15) replacement of filler sand, the compressive strength was comparable with the control mortar. The 7-days compressive strength of 20% waste glass sample was highest among the tested geopolymer mortars made by replacing the filler with waste glass. However, the improvement in flow value with glass did not reflect in their compressive strength test results. This requires further research to draw any definite conclusion in this regard.

3.3 Failure Pattern Under Compressive Load

The mortar sample under compressive loading should follow a good pattern to confirm the interface was built satisfactorily. The mortar sample's fracture pattern was examined visually to determine whether it is satisfactory. The failure area of the mortar ascertains those failure patterns. According to [24], both satisfactory and unsatisfactory failure was observed in the samples tested (Fig. 7). Brick dust and EN sand samples provide acceptable failure, and waste glass provides both satisfactory

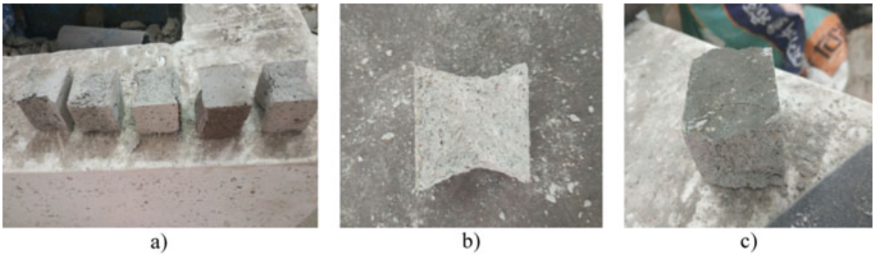

Fig. 7 **a** Geopolymer mortar after the compression test, **b** Satisfactory failure, and **c** Unsatisfactory failure

and unsatisfactory failure. In the case of fly ash, maximum test samples display unsatisfactory failure. This failure occurs not because of the fault in the testing machine or insufficient attention to the testing procedure especially positioning of the specimen as stated by BS EN 12390-3 [25]. This indicates the influence of compaction. The samples gave satisfactory failure, had a better flow, and significantly improved their compressive strength.

3.4 *Environmental and Economic Considerations*

The study indicates that there is a considerable possibility of using industrial by-products in the construction sector. Geopolymer is an eco-friendly alternative binder. Almost one ton of carbon dioxide (CO_2) emits into the ambience from the production of one-ton cement [21]. Fly ash, waste glass, and brick dust are not easily biodegradable. Therefore, without disposing of these waste materials in the construction industry, the betterment of the environment is done by saving the landfill area, conserving the virgin materials, and reducing greenhouse gas production. Among the used filler replacement, 20% brick dust gave the best promising results in geopolymer mortars. In addition, a 20% replacement of filler with waste glass could also be a better way of using this in a cementitious system.

In the local market of Bangladesh, sand costs 45 BDT/cft while brick dust, waste glass, and fly ash costs roughly 5–10 BDT/cft (transport cost only), 100 BDT/cft [19], and 20–25 BDT/cft (transport cost mainly). Therefore, considering a 20% replacement of sand by brick dust can reduce the geopolymer mortar production cost by 30–35%. As the strength improvement was found more than 200%, this was also contending in the estimation. Brick dust is generally found in construction sites after grinding brick to prepare brick chips. Fly ash is a by-product of coal, GGBS is a by-product of the steel industry, and silica fume is a by-product of silicon and ferrosilicon alloy. As an imported material, the price of silica fume in Bangladesh is higher than cement. However, the geopolymer mortar production cost with this binding material (a combination of silica fume, GGBS, and alkaline solution) will be

20–30% lower than cement, comparing the recent price of cement is 480 BDT/50 kg bag in the local market of Bangladesh [19].

4 Conclusion

This research focused on the performance of different filler materials in GGBS and silica fume-based geopolymer mortars. In general, the workability of geopolymer mortars was increased with the amount of filler replacement by various materials. However, fly ash gave the opposite trend due to high surface area and water demand. In most cases, the compressive strengths of geopolymer mortars were improved with time (3 days to 7 days). The strength was generally enhanced with an increase in filler replacement level. Brick dust was found to be efficient filler material. The workability was similar to the control mix until 20% replacement of filler sand by brick dust. Compressive strength improvement of more than 200% was very promising and therefore marked as an eco-friendly material for geopolymer production. Due to the high surface area, the replacement of filler by fly ash did not give better performance than the control mortar. From an economic and environmental perspective, both waste glass and brick dust could be an excellent option for a filler in concrete construction.

Acknowledgements The authors would like to express a sincere appreciation and heartfelt thanks to Consol Limited and Royal Cement, Barapukuria coal power plant for supplying micro silica, GGBS and fly ash for the experimental work, respectively. Furthermore, sincere thanks go to the coordinators of cement testing cell, Engineering Materials Laboratory, Department of Civil Engineering, CUET, for allowing laboratory work for different stages of the research.

References

1. Jaskula, B.B.W.: Mineral Commodity Summary 2014—Gallium. US Geol. Surv. (2014)
2. Gartner, E.: Industrially interesting approaches to 'low-CO_2' cements. Cem. Concr. Res. **34**(9), 1489–1498 (2004)
3. Komljenović, M., Baščarević, Z., Bradić, V.: Mechanical and microstructural properties of alkali-activated fly ash geopolymers. J. Hazard. Mater. **181**(1–3), 35–42 (2010)
4. Part, W.K., Ramli, M., Cheah, C.B.: An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Constr. Build. Mater. **77**, 370–395 (2015)
5. Lyon, R.E., Balaguru, P.N., Foden, A., Sorathia, U., Davidovits, J., Davidovics, M.: Fire-resistant aluminosilicate composites. Fire Mater. **21**(2), 67–73 (1997)
6. Lee, N.K., Jang, J.G., Lee, H.K.: Shrinkage characteristics of alkali-activated fly ash/slag paste and mortar at early ages. Cem. Concr. Compos. **53**, 239–248 (2014)
7. Kong, D.L.Y., Sanjayan, J.G.: Damage behavior of geopolymer composites exposed to elevated temperatures. Cem. Concr. Compos. **30**(10), 986–991 (2008)
8. Huseien, G.F., Mirza, J., Ismail, M., Ghoshal, S.K., Ariffin, M.A.M.: Effect of metakaolin replaced granulated blast furnace slag on fresh and early strength properties of geopolymer mortar. Ain Shams Eng. J. **9**(4), 1557–1566 (2018)

9. Verdolotti, L., Lannace, S., Lavorgna, M., Lamanna, R.: Geopolymerization reaction to consolidate incoherent pozzolanic soil. J. Mater. Sci. **43**(3), 865–873 (2008)
10. Ng, C., Alengaram, U.J., Wong, L.S., Mo, K.H., Jumaat, M.Z., Ramesh, S.: A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. Constr. Build. Mater. **186**, 550–576 (2018)
11. Islam, A., Alengaram, U.J., Jumaat, M.Z., Bashar, I.I.: The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. Mater. Des. **56**, 833–841 (2014)
12. Davidovits, J.: Geopolymers. J. Therm. Anal. **37**(8), 1633–1656 (1991)
13. Erdoğdu, P.T.K.: Effects of fly ash particle size on strength of Portland. **28**(9), 1217–1222 (1998)
14. Andrew, S., William, K.: Lightweight Concrete, 3rd ed. Applied Science Library (1978)
15. Ashraf, M.A., Maah, M.J., Yusoff, I., Wajid, A., Mahmood, K.: Sand mining effects, causes and concerns: a case study from bestari jaya, Selangor, Peninsular Malaysia. Sci. Res. Essays **6**(6), 1216–1231 (2011)
16. Sreenivasa, G.: Use of manufactured sand in concrete and construction an alternate to river sand. India, 2012
17. BDS EN: EN 196–1, Determination of strength. Methods Test. Cem. (2016)
18. BS EN 196–1: Methods of testing cement. Determination of strength. British Standards Institution-BSI and CEN European Committee for Standardization (2005)
19. Islam, G.M.S., Rahman, M.H., Kazi, N.: Waste glass powder as partial replacement of cement for sustainable concrete practice. Int. J. Sustain. Built. Environ. **6**(1), 37–44 (2017)
20. Nochaiya, T., Wongkeo, W., Chaipanich, A.: Utilization of fly ash with silica fume and properties of Portland cement-fly ash-silica fume concrete. Fuel **89**(3), 768–774 (2010)
21. Islam, G.M.S., Islam, M.M., Akter, A., Islam, M.S.: Green construction materials—Bangladesh perspective. In: International Conference on Mechanical Engineering and Renewable Energy (ICMERE2011), 2011
22. Li, L.G., Lin, Z.H., Chen, G.M., Kwan, A.K.H.: Reutilizing clay brick dust as paste substitution to produce environment-friendly durable mortar. J. Clean. Prod. **274**, 122787 (2020)
23. Al-Majidi, M.H., Lampropoulos, A., Cundy, A., Meikle, S.: Development of geopolymer mortar under ambient temperature for in situ applications. Constr. Build. Mater. **120**, 198–211 (2016)
24. Muhamad, K., Hamiruddin, N.A., Razak, R. A.: Effect of steel fibre contents with high strength fibre reinforced concrete. Int. J. Adv. Sci. Res. Eng. (2018)
25. BS EN: 12390-3. Testing Hardened Concrete—Compressive Strength of Test Specimens. British Standards Institution, London, UK (2019)