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# Ternary combined industrial wastes for non-fired brick

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# Ternary combined industrial wastes for non-fired brick


## Abstract

The demand for bricks in South Asia is increasing significantly due to growth in the construction sector. Bricks produced using traditional firing technique and fertile clay contributes significantly to some of the worst air pollution in the world. Therefore, the utilisation of other environment-friendly alternative to conventional bricks is considered an urgent need to conserve a clean environment and help in saving its fertile soil. This research aimed to explore geopolymerization technique with ternary combined industrial waste/by-products as binders including high volume Ladle Furnace Slag (LFS), Fly ash and Ground Granulated Blast Furnace Slag (GGBS) to produce non-fired and clay-free brick alternatives. The first two byproducts are locally produced in the related iron and power industry while GGBS are being imported by the cement industry. The results indicated that all the prepared samples conform to the minimum compressive strength requirement of 20.7 MPa and maximum water absorption rate of 17% for common brick with severe weathering as per ASTM C62. This highly promising performance pronounced the use of locally available high volume LFS and other industrial waste/by-products materials in non-fired building block production to achieve a cleaner, environmental friendly sustainable society as well as a sustainable route for industrial waste management.



**Keywords**: Brick, Cement/cementitious materials; Chemical properties; Composite materials, Fly ash; Ground Granulated Blast Furnace Slag; Ladle furnace slag.

## 1. Introduction

The brick industry has been playing a considerable role in the construction industry for thousands of years. Dating back to 7,000 BC, hand-moulded and sun-dried brick production was found in southern Turkey, the city of Jericho (Brick Architecture, 2017). Utilisation of fire in the production of clay bricks is believed to be around 4500 BC (Smith, Bingel and Bown, 2016). Since then, brick industry has been developing using modern machinery such as tunnel kilns and powerful excavation equipment which have considerably improved the quality and increased the capacity of brick production (Zhang *et al.*, 2018).

The annual production of conventional fired brick reached approximately 1500 billion pieces worldwide (Climate and Clean Air Coalition, 2016; Zhang *et al.*, 2018). Generally, the brick industry has always been a resource and energy intensive (Amaral *et al.*, 2013; Li *et al.*, 2015; Weishi *et al.*, 2018). Study found the production of one brick requires 2.0 kWh energy while this associates approximately 0.4 kg of $CO_2$ emission (Muñoz Velasco *et al.*, 2014). Therefore, conventional fired brick production challenges the requirement of sustainable development (Wu *et al.*, 2012). Apart from that, the densely populated country Bangladesh is losing approximately 1% of agricultural land annually (Dhaka Tribune, 2016). Approximately 17% of that soil is being used in brick production and the rest is attributed to unplanned rural housing (Editorial, 2016). The reported annual production of conventional bricks in Bangladesh is about 25 billion, damaging approximately 100 million tonnes of topsoil. Therefore, the potential impact of this process has a devastating effect on the environment (Correspondent, 2018).

Air quality of Dhaka (capital of Bangladesh) is reported as the third worst in the world, after Delhi and Cairo (WHO, 2016). Approximately 58% air pollution of this city is attributed to brick manufacturing and the situation is getting worsened as very few of these brick kilns have been constructed following proper design and environmental rules (Editorial, 2016; Dhaka Tribune, 2019). The country therefore, is in an urgent need to utilise environmentally-friendly alternative technology/material. Incorporating industrial waste/byproducts for brick production without firing can save fertile topsoil and conserve the environment for sustainable development.

Considering both environmental and economic issues an alternative to the conventional bricks could be the use of Portland Cement (PC), sand and waste materials to produce concrete bricks. However, the cement clinker production is energy intensive; production of 1 kg clinker requires approximately 1.5 kg of raw materials and releases up to 1 kg of $CO_2$ to the atmosphere (Islam and Islam, 2015; Binhowimal, Hanzic and Ho, 2017). Cement industry is responsible for approximately 7% $CO_2$ emission over the world (Islam, Mondal and Islam, 2010; Hawileh *et al.*, 2017). Therefore, production of cement based building blocks is not a sustainable alternative solution.

The steel industries in Bangladesh are mainly based around Chittagong city (where this research was conducted) (Rahman *et al.*, 2017). This sector is expected to thrive due to the rapid expansion of various steel based projects, shipbuilding and real estate sector (Rahman *et al.*, 2017). Bangladeshi steel industries uses 4000000 tons of raw materials to produce required steel (Report, 2018). The steelmaking process produces approximately 130-200 kg of various kinds of slags (Furlani, Tonello and Maschio, 2010). This anticipated expansion will enviably be an increase in the amount of byproduct materials from this industry. Ladle Furnace Slag (LFS), Induction Furnace Slag (IFS) and Ground Granulated Blast Furnace Slag (GGBS) are general by-products of steel industry. GGBS has been introduced in cement or brick production due to its desirable properties (Oti, Kinuthia and Bai, 2008). However, the use of LFS (produced at least 30 kg/ton of steel production) in the construction industry gained less attention and generally being dumped as landfill (Manso *et al.*, 2005; Adesanya *et al.*, 2020).

Fly ash is another industrial byproduct from coal based power plants. Every year approximately 109,200 tonnes of fly ash is being produced in Bangladesh which will rise to 865,000 tonnes per year by 2024 (Islam *et al.*, 2019). For a densely populated country, fly ash and steel byproducts will sum up an enormous amount to dispose and is a great concern for the authority (Islam *et al.*, 2011). Considering the chemical composition of LFS, GGBS and Fly ash, the byproducts could be reused to reduce landfills and for the economic reservation of virgin materials (Češnovar *et al.*, 2019).

Researchers have studied bricks production from waste/by-products through alkali-activation (geopolymerisation) (Zhang, 2013). Alkali-activated materials are inorganic materials with ceramic-like properties; produced by poly-condensation of raw materials (usually rich in silica and alumina) with alkaline solution at ambient or slightly higher temperatures (Vafaei *et al.*, 2018; Paija *et al.*, 2020). Researchers have studied various waste/by-product materials for the production of alkali activated materials, including red mud and metakaolin (He *et al.*, 2012), fly ash and mine tailings (Zhang, Ahmari and Zhang, 2011), type F fly ash (Arıöz *et al.*, 2010), copper mine tailings (Ahmari and Zhang, 2012), fly ash and GGBS (Lawrence, Sugo and Page, 2008; Prakasam, Murthy and Saffiq Reheman, 2020), LFS (Manso *et al.*, 2005; Adesanya *et al.*, 2020) and waste concrete (Mahakavi and Chithra, 2019). However, the combined utilisation of locally available high volume (up to 60%) LFS along with Fly ash and GGBS in the production of alkali activated brick could be a novel approach. Therefore, the alkali-activation technique using high volume LFS along with other industrial by-products (fly ash and GGBS) is considered in this research for the production of non-fired, clay-free eco-friendly brick for Bangladesh.

# 2. Materials and Methodology

## 2.1 Material

### 2.1.1 Aggregate

River sand obtained from local source was used as fine aggregate. Controlled grading of the sand was used to avoid any experimental variation due to size of the sand. Cumulative percentages of the material passing through ASTM standard sieves #16, #30, #50 and #100 (ASTM, 2019a) are 100, 75, 25 and 0 respectively. Bulk specific gravity, absorption capacity, fineness modulus and field moisture content of the river sand are found to be 2.55, 1.66%, 2.00 and 0.68%, respectively.

### 2.1.2 Alkaline activators

Preliminary tests were carried out on a single ternary combination of binders with 4M, 6M and 8M concentration alkali activators. The test results indicated with a 4M combined concentration of Sodium hydroxide (NaOH) solution and Sodium silicate solution ($Na_2SiO_3$) the geopolymer mortars achieved 45-50 MPa compressive strength. The $Na_2SiO_3$ solution consisted of 51.75% $H_2O$, 32.75% $SiO_2$ and15.50% $Na_2O$, by weight. The use of NaOH and $Na_2SiO_3$ together in the production of alkali activated brick is essential to ensure good mechanical and durability performance as $Na_2SiO_3$ acts as binder or alkali reactant while NaOH is required for the dissolution of alumina-silicate precursor (Xu and Van Deventer, 2002; Wang, Li and Yan, 2005; Feng, Provis and Deventer, 2012; Liew *et al.*, 2016).

### 2.1.3 Water

Ordinary tap water was used in this research.

### 2.1.4 Binder materials

The binder materials utilised in this research were LFS, Fly ash and GGBS from local Bangladeshi sources. The LFS and GGBS were obtained from Bangladesh Steel Re-rolling Mills and Royal Cement Limited, respectively while the fly ash was obtained from Barapukuria Coal Burning Power Plant. Chemical compositions of the binder materials were determined using X-ray Florescence Spectrometer (XRF) type Shimadzu EDX-720 given in Table 1. The chemical composition of fly ash satisfies the criteria of being low calcium fly ash (Class F) according to ASTM C618 (ASTM, 2019b). LFS and GGBS have high CaO and $SiO_2$ content therefore, calcium silicate hydrates (C-S-H) gel is anticipated to be formed within the hydration products in conjunction with geoploymeric gel (Yip and Van Deventer, 2003; Yunsheng *et al.*, 2007; Liew *et al.*, 2016). XRD patterns of the binder samples obtained using a Rigaku Miniflex desktop type are given in Fig. 1. Each sample was analysed over the 2θ range of 3-60° at a scan rate of 1°/minute with 0.1 degree increments. Obtained XRD data was used to match with Powder Diffraction File (PDF) of minerals with the help of computer software. The results are indication of the quantity of specific phases present in the materials. It should be noted that, the method gives only an estimate of the minerals phase present in the materials. As shown in Fig. 1, the dominant minerals found in LFS were Calcio-olivine, Akermanite, and Alpha Quartz low. While this was Mullite and Quartz for fly ash and Akermanite for GGBS.

The physical size of the binder materials were evaluated through Particle Size Distribution (PSD) and Specific Surface Area (SSA) tests. The PSD was determined by Beckman Coulter laser particle size analyser while the SSA was determined by Blaine air-permeability apparatus.

The PSD of binder materials are given in Fig. 2 while other physical properties are presented in Table 2.

## 2.2 Mix details and preparation of the alkali-activated mortars

For the production of the alkali-activated mortars, LFS was blended with fly ash and GGBS in different ratio as given in Table 3. The major oxide ratio was calculated later to explore their relationship with compressive strength obtained from the experimental results. For all the combinations, the sand to binder (S/B) ratio was kept as 2 while the alkali activator to binder (A/B) ratio and the Sodium Silicate to Sodium Hydroxide ratio were fixed at 0.5 and 2, respectively. Additional water to binder (W/B) ratio of 0.1 was supplied for all mixtures to make the mixture workable. Higher quantity of water can hinder polycondensation of the alkali-activated binder due to its dilution effect (Zuhua *et al.*, 2009; Kim, Yi and Kang, 2015).

The prepared mortar samples' dimensions was 40 × 40 × 160 mm as per BDS EN 196-1:2003 (BDS EN, 2016). Prime aim of this work is to establish mix details to achieve minimum compressive strength required for non-fired bricks. Therefore, the mortar specimen size was kept conforming to compressive strength test standards. The required ingredients were mixed with an automatic mortar mixture following ~~standard procedure described in~~ BDS EN 196-1 (BDS EN, 2016).

After mixing the content was transferred to the steel moulds and compacted in two layers. Each layer was compacted for 60s by a mechanical jolt. After compaction, ~~all~~ the specimens were kept inside the mould and the exposed surfaces were sealed with a plastic food cover sheet. The moulds were then placed in an air-conditioned chamber ~~having~~ maintaining a constant temperature (23±2°C) and relative humidity (50-60%) for the next 1 day prior to placing for elevated temperature curing in oven. Then after a successful demoulding process, four samples from each mixture were heat cured for 18 hours at 60ºC in an oven. After 18 hours of heat curing, three samples was tested for compressive strength and other three were kept in room constant temperature (23±2°C) by wrapping with the plastic food cover sheet to avoid moisture loss until 7 days and then strength test was carried out. Different stages of alkali activated mortar preparation are given in Fig. 3.

### 2.3 Programme of Testing

#### 2.3.1 Compressive strength test

Compressive strength test of mortar samples was conducted as per BDS EN 196-1:2003 (BDS EN, 2016) using a compressive strength testing machine. As the loading area was only 40×40 mm, an internal jig was applied inside the compression testing machine. For each sample, two maximum dial load readings were reported and the average value of four reading from each mix was used for comparison purposes.

#### 2.3.2 Water Absorption test

Water absorption is a very important property that usually determines the durability performance of a bricks. The water absorption test is considered as a measurement to the compactness of bricks and it can provide direct measurement to the resistance of bricks to damage by freezing. The water absorption test was conducted according to ASTM C67 (ASTM, 2020) at the age of 7 days. For each mixture three cooled specimens were submerged in clean water (soft, distilled or rain water) at 15.5-30°C for 24 hours without preliminary partial immersion. The specimens were then shifted to boiling water for 5 hours and the mean water absorption (%) was determined.

### 2.3.3 Scanning Electron Microscopy (SEM) observation

High magnification image micrographs of binder materials were obtain by SEM. Morphology was obtained using an EDX Oxford Inca x-act detector, an FEI SEM model Inspect S and a Quanta 200 with an accelerating voltage of 5–20 kV. Additionally, the SEM testing was conducted for the paste of the optimum combination of the binder materials after 18 hours and 7 days curing. Double sided adhesive carbon tape was secured to a 10 mm diameter aluminium stub and the sample sprinkled on it. It is worth mentioning that the samples used for the SEM testing were casted especially for this purpose and the specimens were polished before starting the test to improve the visibility and to easily compare the cracks, porosity and density of the samples.

## 3. Results and Discussion

### 3.1 Compressive strength

Compressive strength is considered as the most important property of building bricks. The specifications for severe weathering (SW) case require a minimum compressive strength of 20.7 MPa for clay or shale bricks (ASTM, 2017). Compressive strength results obtained from different ternary mixtures are given in Fig. 4. The 18 hours and 7 days compressive strength was found to be more or less similar for all mixtures. The results indicated that the alkali-activated mixture having 40% LFS 20% fly ash and 40% GGBS (T3) has the highest compressive strength than any other mixture and the lowest compressive strength was obtained with batch T5 having 60% LFS, 20% fly ash and 20% GGBS.

As shown in Fig. 4 the effect of ambient temperature curing after 18 hours of heat curing is insignificant. The slight reduction in compressive strength after 7 days compared to that after 18 hours is believed to be due to the fast gel formation as a results of elevated temperature curing that leads to chemical deformation (expansion) and resulting in lower compressive strength (Wang, Wang and Tsai, 2016; Češnovar *et al.*, 2019). As shown in Fig. 4, the compressive strength obtained after heat curing for 18 hours did not improved much after keeping this at ambient temperature until 7 days. This indicates either of these ternary combinations could achieve minimum requirement specified by ASTM C62 (ASTM, 2017) and therefore within a minimum possible time a sustainable and alternative building blocks could be prepared.

The results indicated that for a fixed level of LFS (40%), increasing the GGBS content and reducing the Fly ash content gave higher compressive strength. Also keeping LFS content fixed at 40% of total binder content and replacing 20% of Fly ash by GGBS (T3) gave almost double strength than that with 40% Fly ash and 20% GGBS (T1). This could be attributed to both (i) the formation of more C-S-H gel simultaneously with the geopolymeric gel as the GGBS has higher calcium content relative to Fly ash (Provis *et al.*, 2012; Rakhimova and Rakhimov, 2015) and (ii) to the finer particles and higher SSA of GGBS relative to Fly ash that enhanced the performance of the bricks during geopolymerisation reaction as reported in earlier study (Gunasekara, Law and Setunage, 2016).

Fixing the GGBS content at 20% of total binder content and the increase of Fly ash replacement level by LFS the compressive strength was found to be decreased. This could be due to the larger particles and lower SSA of LSF in comparison with the Fly ash (Adolfsson *et al.*, 2007; Islam *et al.*, 2011). The overall results indicated that all the mixtures have satisfied a minimum compressive strength requirement for common bricks with severe weathering according to ASTM C62 (ASTM, 2017) only after 18 hours of heat curing. This promising high early strength gaining of alkali-activated non-fired bricks indicates the potential for adapting high strength non-fired brick production with waste/by-product materials as alternative to conventional fired clay bricks.

### 3.1.1 Compressive strength and chemical composition

Further analysis was carried out to explore if there is any relationship between the overall chemical composition of the ternary blended binders and corresponding compressive strength achieved at 18 hours and 7 days. Figs. 5-7 show the relationship between compressive strengths and $SiO_2/Al_2O_3$, $H_2O/Na_2O$ and $Na_2O/SiO_2$ molar ratios respectively. The error bars of compressive strength measurement are given in all figures. As shown in Fig. 4 earlier the difference between 18 hour and 7 days compressive strength test results were very close. According to Figs. 5 and 6, strong power correlation was found between compressive strength and both $SiO_2/Al_2O_3$, $H_2O/Na_2O$ molar ratios. With increase in these molar ratios the compressive strength was found to be decreasing in nature. In contrary, though the trend was not definite an increase in compressive strength was obtained with $Na_2O/SiO_2$ molar ratio. Earlier study (Valencia-Saavedra, Mejía de Gutiérrez and Puertas, 2020) with two samples reported similar trend of compressive strength with $SiO_2/Al_2O_3$ and $Na_2O/SiO_2$. As shown in Figs. 5 and 6 the trend indicates further test with lower molar ratios of other ternary combination could strengthen this relationship.

## 3.2 Water Absorption

The water absorption test was conducted as per ASTM C67 at the age of 7 days. The alkali-activated bricks were submerged in boiling water for 5 hours followed by normal water immersion for 24 hours ~~is~~ (results given in Fig. 8). Resultes of the water absortion test was found to be consistent with compressive strength. Incresing the GGBS content in the mixtuture resulted in reduced water absorption while water absorption rate incresed with the LFS content in the mixture. The lowest water absoprion rate was obtained for mixture T3 (40% LFS, 20% fly ash and 40% GGBS) and the heighest water absorption rate was recorded for the mixture T5 (60% LFS, 20% fly ash and 20% GGBS). This behabiour could be attributed to the the finer particles and the high SSA of the GGBS relative to LFS particles that enhanced the performance of the bricks during geopolymerization activity (Gunasekara, Law and Setunage, 2016; Roychand, De Silva and Setunge, 2018).

Generally, all the alkali-activated bricks gave very low water absorption. This was well satisfied the requirements for common bricks with severe weathering according to ASTM C62 which limits the maximum water absoprtion rate upto 17% (ASTM, 2017). This low water absorption rate could be attributed to a succussful geopolymerisation reaction and thereby formation of very dense microstructure that resulted in the formation of less pores. Additionally, this low water absorption rate is attributed to a better packing between the binder materials and the fine aggregate that resulted from a good interlocking of the mixture (Jain, Gupta and Chaudhary, 2019).

According to the results of the compressive strength and water absoprion, the utilisation of upto 60% LFS satisfied the requirment for compressive strength and water absoprtion for SW condition common bricks. As the mixture T3 (40% LFS, 20% fly ash and 40% GGBS) showed the highest compressive strength and the lowest water absportion rate it was chooesn as the optimum mixture. This mixture was then used for subsequent microstructure investigation using SEM.

### 3.3 Microstructure Observations using SEM

SEM imaging technique has been increasingly employed in cement, concrete and brick research, especially for microstructural investigation. Changes in the microstructure over curing time could be distinguished using SEM (Kovler, 1998; Tagnit-Hamou, Vanhove and Petrov, 2005; Roychand, De Silva and Setunge, 2018). In addition, the test can provide information on the morphology of the hydrated phases of binders (Rossen and Scrivener, 2017). In this research, SEM was used to relate the performance of binder materials in the production of alkali-activated bricks (Scrivener, Snellings and Lothenbach, 2017). The SEM images of the Fly ash, GGBS and LFS are shown in Fig. 9. Fly ash particles generally consist of spherical shape with some irregular shape particles. On the other hand, the GGBS and LFS consists angular and flaky shape particles with some irregular shape particles. In addition, the LFS particles were generally found to be coarser than that of Fly ash and GGBS particles, thus SEM images agrees with PSD results (Fig. 2).

Fig. 10 shows the SEM micrographs of the T3 paste after 18 hours (high temperature) and 7 days (ambinent after high temperature) of curing. SEM imaging after 18 hours of heat curing (Fig. 10a) shows the formation of geopolymer gel at early ages. The microstructure was found to be homogeneous with some associated microcracks. An unreacted particle of FA is appeared to present at down left corner in Fig. 10a. Increasing the period of curing to 7 days resulted in the formation of denser microstructure with gel appears evenly distributed covering most of the T3 paste surface while the associated microcracks were also present. Similar to Fig 10a, potential presence of an unreacted slag particle was appeared at the upright corned of Fig. 10b. Generally, in high CaO content system C-S-H gel forms simultaneously with geopolymer gel, however, C-S-H gel forms slower than geopolymer gel (Ahmari and Zhang, 2013). This is the reason behind the formation of denser microstructure after 7 days of curing relative to that after 18 hours of.

Additionally, the formation of microcracks could be due to the continuous moisture loss from the specimens within the curing period that resulted in the slight reduction in the compressive strength as given in Fig. 4. Similar observations were reported by (Leong *et al.*, 2018). These observations were consistent with the results of the compressive strength and water absorption of the T3 alkali activated brick (shown in Fig. 5).

## 4. Practical Implications

The study has established potential ternary combination of various industrial waste materials could be used to produce alternative to conventional clay fired bricks. The waste products viz. fly ash, GGBS and ladle furnace slag are management concern for the producers. At the same time conventional brick kilns are potential source of severe air pollution and consumed mainly virgin raw materials. This study therefore, would help the related industry management to explore alternative option for utilizing the waste and conserving the environment. Economic analysis of geopolymer brick using combination of natural aggregate/material and waste brick by a French study (Youssef, Lafhaj and Chapiseau, 2020) indicated 5% cost saving from traditional clay fired brick. With a similar cost the compressive strength of geopolymer brick (39 MPa) using waste brick could be doubled up from control sample. In this study sample T3 (Fig. 4) with considerable amount of fly ash and other industrial waste (with embodied energy/carbon) in the mixture gave compressive strength of 51.5 MPa. The insignificant $CO_2$ emissions associated with the production of geopolymer brick would be only from the transportation of the industrial waste materials without burning any fossil fuel (required for heat curing of traditional clay fired brick). This could be further optimized using induction furnace slag (another iron industry by product) instead of natural sand and reducing the strength of alkaline activator as the strength requirement (ASTM, 2017) for brick is almost one-third of that achieved in this study. Based on this study entrepreneurs could decide to initiate brick/building block industry to produce commercial non-fired bricks using these potential materials.

## 5. Conclusion

The aim of this research was to explore alkali-activation technique to produce non-fired bricks/building blocks using locally available high volume LFS and other industrial solid by-products including fly ash and GGBS. Compressive strength, water absorption and SEM microstructure imaging tests were conducted to evaluate the performance of the mixtures. The following specific conclusion was obtained from this study:

- Each ternary combined mixture conformed to the the compressive strength requirememnt according to ASTM C62 for common bricks with severe weathering. The water absorption rate was also found well below the range for common bricks with severe weathering according to ASTM C62. The compressiv stength obtained at 18 hours heat curing did not improve significantly after keeping these in ambient environment for 7 days.
- Good correlation was found between compressive strength of produced blocks and both $SiO_2/Al_2O_3$, $H_2O/Na_2O$ molar ratios at both 18 hour and 7 days age. With increase in these molar ratios the compressive strength was found to be decreasing.
- Incresing the LFS content resulted in deacresing the compressive strength and incresing the water absorption rate. However, by replacing fly ash with GGBS, strength increased for a certain percentage of LFS (40% of total binder) content.

- The maximum compressive strength and the minmum water absorption rate was achived with 40% LFS, 20% Fly ash and 40% GGBS binder combination (T3). Further investigation of T3 with SEM imaging reveled compacted and hudrated microstructure with minor microcracks at both 18 h and 7 days curing.

From the experimental works conducted in this research it was concluded that geopolymerization with a binder combination of 40% LFS, 20% Fly ash, 40% GGBS content could be a sustainable option for the production of non-fired bricks. Further study could be carried out to quantify the reaction product as well as unreacted materials present in the mix using EDS, FTIR and XRD combination though it was not within the scope of this study.

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## Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

## References

Adesanya, E. *et al.* (2020) 'Thermal behaviour of ladle slag mortars containing ferrochrome slag aggregates', *Advances in Cement Research*. Thomas Telford Ltd., pp. 1–15. doi: 10.1680/jadcr.19.00040.

Adolfsson, D. *et al.* (2007) 'Steelmaking slags as raw material for sulphoaluminate belite cement', *Advances in Cement Research*. Thomas Telford Ltd , 19(4), pp. 147–156. doi: 10.1680/adcr.2007.19.4.147.

Ahmari, S. and Zhang, L. (2012) 'Production of eco-friendly bricks from copper mine tailings through geopolymerization', *Construction and Building Materials*. Elsevier, 29, pp. 323–331. doi: 10.1016/j.conbuildmat.2011.10.048.

Ahmari, S. and Zhang, L. (2013) 'Utilization of cement kiln dust (CKD) to enhance mine tailings-based geopolymer bricks', *Construction and Building Materials*. Elsevier, 40, pp. 1002–1011. doi: 10.1016/j.conbuildmat.2012.11.069.

Amaral, M. C. *et al.* (2013) 'Soil-cement bricks incorporated with eggshell waste', *Proceedings of Institution of Civil Engineers: Waste and Resource Management*. ICE Publishing , 166(3), pp. 137–141. doi: 10.1680/warm.12.00024.

Arıöz, O. *et al.* (2010) 'Physical, Mechanical and Micro-Structural Properties of F Type Fly-Ash Based Geopolymeric Bricks Produced by Pressure Forming Process', *Advances in Science and Technology*, 69, pp. 69–74. doi: https://doi.org/10.4028/www.scientific.net/AST.69.69.

ASTM (2017) 'ASTM C62, Standard specification for building brick (solid masonry units made from clay or shale)', *Annual Book of ASTM Standards*. West Conshohocken, PA, USA. doi: 10.1520/C0062-17.

ASTM (2019a) 'ASTM C136/C136M, Standard test method for sieve analysis of fine and coarse aggregates', *Annual Book of ASTM Standards*. West Conshohocken, PA, USA. doi: 10.1520/C0136_C0136M-19.

ASTM (2019b) *ASTM C618, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*, *Annual Book of ASTM Standards*. West Conshohocken, PA, USA. doi: 10.1520/C0618-19.

ASTM (2020) *ASTM C67/C67M, Standard test methods for sampling and testing brick and structural clay tile*, *Annual Book of ASTM Standards*. West Conshohocken, PA, USA. doi: 10.1520/C0067_C0067M-20.

BDS EN (2016) 'EN 196-1, Determination of strength', *Methods of testing cement.* BSTI, Bangladesh.

Binhowimal, S. A. M., Hanzic, L. and Ho, J. C. M. (2017) 'Filler to improve concurrent flowability and segregation performance of concrete', *Australian Journal of Structural Engineering*. Taylor and Francis Ltd., 18(2), pp. 73–85. doi: 10.1080/13287982.2017.1333184.

Brick Architecture (2017) *The history of bricks and brickmaking*. Available at: https://brickarchitecture.com/about-brick/why-brick/the-history-of-bricks-brickmaking#:~:text=without visible joints-,The History of Bricks and Brickmaking,around the city of Jericho. (Accessed: 29 July 2020).

Češnovar *et al.* (2019) 'The Potential of Ladle Slag and Electric Arc Furnace Slag use in

Synthesizing Alkali Activated Materials; the Influence of Curing on Mechanical Properties', *Materials*. MDPI AG, 12(7), p. 1173. doi: 10.3390/ma12071173.

Climate and Clean Air Coalition (2016) *Mitigating black carbon and other pollutants from brick production*. Available at: www.ccacoalition.org/en/initiatives/bricks (Accessed: 31 July 2020).

Correspondent, S. (2018) 'Shun burnt bricks to save topsoil', *The Daily Star*, p. Back page.

Dhaka Tribune (2016) *1% arable land lost each year*. Available at: www.dhakatribune.com/bangladesh/2016/06/17/1-arable-land-lost-year/ (Accessed: 31 July 2020).

Dhaka Tribune (2019) *Environment minister: Brick kilns responsible for 58% air pollution in Dhaka*. Available at: www.dhakatribune.com/bangladesh/environment/2019/02/14/environment-minister-brick-kilns-responsible-for-58-air-pollution-in-dhaka (Accessed: 31 July 2020).

Editorial (2016) 'Brick kilns king among air pollutants', *The Daily Star*.

Feng, D., Provis, J. L. and Deventer, J. S. J. (2012) 'Thermal Activation of Albite for the Synthesis of One-Part Mix Geopolymers', *Journal of the American Ceramic Society*, 95(2), pp. 565–572. doi: 10.1111/j.1551-2916.2011.04925.x.

Furlani, E., Tonello, G. and Maschio, S. (2010) 'Recycling of steel slag and glass cullet from energy saving lamps by fast firing production of ceramics', *Waste Management*. Pergamon, pp. 1714–1719. doi: 10.1016/j.wasman.2010.03.030.

Gunasekara, C., Law, D. W. and Setunage, S. (2016) 'Long term engineering properties of fly ash geopolymer concrete', in *Fourth International Conference on Sustainable Construction Materials and Technologies*. Las Vegas, USA.

Hawileh, R. A. *et al.* (2017) 'Performance of reinforced concrete beams cast with different percentages of GGBS replacement to cement', *Archives of Civil and Mechanical Engineering*. Elsevier B.V., 17(3), pp. 511–519. doi: 10.1016/j.acme.2016.11.006.

He, J. *et al.* (2012) 'The strength and microstructure of two geopolymers derived from metakaolin and red mud-fly ash admixture: A comparative study', *Construction and Building Materials*. Elsevier, 30, pp. 80–91. doi: 10.1016/j.conbuildmat.2011.12.011.

Islam, G. M. S. *et al.* (2011) 'Green Construction Materials – Bangladesh Perspective', in *International Conference on Mechanical Engineering and Renewable Energy (ICMERE2011)*. Chittagong: Department of Mechanical Engineering, CUET, Bangladesh.

Islam, M. M. and Islam, M. S. (2015) 'Strength and Durability Characteristics of Concrete made with Fly-Ash Blended Cement', *Australian Journal of Structural Engineering*, 14(3), pp. 303–319.

Islam, M. R. *et al.* (2019) 'Utilizing Fly Ash to Improve Subgrade Properties in Bangladesh', in *Airfield and Highway Pavements 2019: Testing and Characterization of Pavement Materials - Selected Papers from the International Airfield and Highway Pavements Conference 2019*. American Society of Civil Engineers (ASCE), pp. 522–530. doi: 10.1061/9780784482469.052.

Islam, M. S., Mondal, B. C. and Islam, M. M. (2010) ‘Effect of sea salts on structural concrete in a tidal environment’, *Australian Journal of Structural Engineering*. Engineers Media, 10(3), pp. 237–252. doi: 10.1080/13287982.2010.11465048.

Jain, A., Gupta, R. and Chaudhary, S. (2019) ‘Performance of self-compacting concrete comprising granite cutting waste as fine aggregate’, *Construction and Building Materials*. Elsevier, 221, pp. 539–552.

Kim, B. J., Yi, C. and Kang, K. I. (2015) ‘Microwave curing of alkali-activated binder using hwangtoh without calcination’, *Construction and Building Materials*. Elsevier Ltd, 98, pp. 465–475. doi: 10.1016/j.conbuildmat.2015.08.119.

Kovler, K. (1998) ‘Setting and hardening of gypsum-portland cement-silica fume blends, Part 2: Early strength, DTA, XRD, and SEM observations’, *Cement and Concrete Research*. Elsevier Ltd, 28(4), pp. 523–531. doi: 10.1016/S0008-8846(98)00004-0.

Lawrence, S. J., Sugo, H. O. and Page, A. W. (2008) ‘Masonry bond strength and the effects of supplementary cementitious materials’, in *Australian Journal of Structural Engineering*. Engineers Media, pp. 101–116. doi: 10.1080/13287982.2008.11464991.

Leong, H. Y. *et al.* (2018) ‘Strength Development of Soil–Fly Ash Geopolymer: Assessment of Soil, Fly Ash, Alkali Activators, and Water’, *Journal of Materials in Civil Engineering*. American Society of Civil Engineers (ASCE), 30(8), p. 04018171. doi: 10.1061/(ASCE)MT.1943-5533.0002363.

Li, G. *et al.* (2015) ‘Properties of cement-based bricks with oyster-shells ash’, *Journal of Cleaner Production*. Elsevier Ltd, 91, pp. 279–287. doi: 10.1016/j.jclepro.2014.12.023.

Liew, Y. M. *et al.* (2016) ‘Structure and properties of clay-based geopolymer cements: A review’, *Progress in Materials Science*. Elsevier Ltd, pp. 595–629. doi: 10.1016/j.pmatsci.2016.08.002.

Mahakavi, P. and Chithra, R. (2019) ‘Effect of recycled coarse aggregate and manufactured sand in self compacting concrete’, *Australian Journal of Structural Engineering*. Taylor and Francis Ltd. doi: 10.1080/13287982.2019.1636519.

Manso, J. M. *et al.* (2005) ‘Ladle Furnace Slag in Construction’, *Journal of Materials in Civil Engineering*. American Society of Civil Engineers, 17(5), pp. 513–518. doi: 10.1061/(ASCE)0899-1561(2005)17:5(513).

Muñoz Velasco, P. *et al.* (2014) ‘Fired clay bricks manufactured by adding wastes as sustainable construction material - A review’, *Construction and Building Materials*. Elsevier Ltd, pp. 97–107. doi: 10.1016/j.conbuildmat.2014.03.045.

Oti, J. E., Kinuthia, J. M. and Bai, J. (2008) ‘Using slag for unfired-clay masonry-bricks’, *Proceedings of Institution of Civil Engineers: Construction Materials*. Thomas Telford Ltd , 161(4), pp. 147–155. doi: 10.1680/coma.2008.161.4.147.

Paija, N. *et al.* (2020) ‘Ground Bottom Ash Application for Conventional Mortar and Geopolymer Paste’, *Journal of Hazardous, Toxic, and Radioactive Waste*. American Society of Civil Engineers (ASCE), 24(1), p. 04019025. doi: 10.1061/(ASCE)HZ.2153-5515.0000466.

Prakasam, G., Murthy, A. R. and Saffiq Reheman, M. (2020) ‘Mechanical, durability and fracture properties of nano-modified FA/GGBS geopolymer mortar', *Magazine of Concrete Research*. ICE Publishing, 72(4), pp. 207–216. doi: 10.1680/jmacr.18.00059.

Provis, J. L. *et al.* (2012) 'X-ray microtomography shows pore structure and tortuosity in alkali-activated binders', *Cement and Concrete Research*. Pergamon, 42(6), pp. 855–864. doi: 10.1016/j.cemconres.2012.03.004.

Rahman, M. S. *et al.* (2017) 'Investigation of Heavy Metals and Radionuclide's Impact on Environment Due to The Waste Products of Different Iron Processing Industries in Chittagong, Bangladesh', *Journal of Environmental Protection*. Scientific Research Publishing, Inc, 08(09), pp. 974–989. doi: 10.4236/jep.2017.89061.

Rakhimova, N. R. and Rakhimov, R. Z. (2015) 'Alkali-activated cements and mortars based on blast furnace slag and red clay brick waste', *Materials and Design*. Elsevier Ltd, 85, pp. 324–331. doi: 10.1016/j.matdes.2015.06.182.

Report, S. B. (2018) 'Steel makers call for slash in customs duty, tax', *The Daily Star*.

Rossen, J. E. and Scrivener, K. L. (2017) 'Optimization of SEM-EDS to determine the C–A–S–H composition in matured cement paste samples', *Materials Characterization*, 123, pp. 294–306. doi: 10.1016/j.matchar.2016.11.041.

Roychand, R., De Silva, S. and Setunge, S. (2018) 'Nanosilica Modified High-Volume Fly Ash and Slag Cement Composite: Environmentally Friendly Alternative to OPC', *Journal of Materials in Civil Engineering*. American Society of Civil Engineers (ASCE), 30(4), p. 04018043. doi: 10.1061/(ASCE)MT.1943-5533.0002220.

Scrivener, K., Snellings, R. and Lothenbach, L. (2017) *A practical guide to microstructural analysis of cementitious material*. First Edit. Florida, USA.: CRC Press.

Smith, A. S., Bingel, P. and Bown, A. (2016) 'Sustainability of masonry in construction', in *Sustainability of Construction Materials*. Elsevier, pp. 245–282. doi: 10.1016/b978-0-08-100370-1.00011-1.

Tagnit-Hamou, A., Vanhove, Y. and Petrov, N. (2005) 'Microstructural analysis of the bond mechanism between polyolefin fibers and cement pastes', *Cement and Concrete Research*. Pergamon, 35(2), pp. 364–370. doi: 10.1016/j.cemconres.2004.05.046.

Vafaei, M. *et al.* (2018) 'Acid attack on geopolymer cement mortar based on waste-glass powder and calcium aluminate cement at mild concentration', *Construction and Building Materials*. Elsevier Ltd, 193, pp. 363–372. doi: 10.1016/j.conbuildmat.2018.10.203.

Valencia-Saavedra, W. G., Mejía de Gutiérrez, R. and Puertas, F. (2020) 'Performance of FA-based geopolymer concretes exposed to acetic and sulfuric acids', *Construction and Building Materials*. Elsevier Ltd, 257, p. 119503. doi: 10.1016/j.conbuildmat.2020.119503.

Wang, H., Li, H. and Yan, F. (2005) 'Synthesis and mechanical properties of metakaolinite-based geopolymer', *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. Elsevier, 268(1–3), pp. 1–6. doi: 10.1016/j.colsurfa.2005.01.016.

Wang, W. C., Wang, H. Y. and Tsai, H. C. (2016) 'Study on engineering properties of alkali-activated ladle furnace slag geopolymer', *Construction and Building Materials*. Elsevier Ltd, 123, pp. 800–805. doi: 10.1016/j.conbuildmat.2016.07.068.

Weishi, L. *et al.* (2018) 'The properties and formation mechanisms of eco-friendly brick building materials fabricated from low-silicon iron ore tailings', *Journal of Cleaner Production*. Elsevier Ltd, 204, pp. 685–692. doi: 10.1016/j.jclepro.2018.08.309.

WHO (2016) *Ambient air pollution: A global assessment of exposure and burden of disease*. World Health Organization.

Wu, H. J. *et al.* (2012) 'Life cycle energy consumption and CO2 emission of an office building in China', *International Journal of Life Cycle Assessment*. Springer Verlag, pp. 105–118. doi: 10.1007/s11367-011-0342-2.

Xu, H. and Van Deventer, J. S. J. (2002) 'Geopolymerisation of multiple minerals', *Minerals Engineering*. Pergamon, 15(12), pp. 1131–1139. doi: 10.1016/S0892-6875(02)00255-8.

Yip, C. K. and Van Deventer, J. S. J. (2003) 'Microanalysis of calcium silicate hydrate gel formed within a geopolymeric binder', *Journal of Materials Science*. Springer, 38(18), pp. 3851–3860. doi: 10.1023/A:1025904905176.

Youssef, N., Lafhaj, Z. and Chapiseau, C. (2020) 'Economic Analysis of Geopolymer Brick Manufacturing: A French Case Study', *Sustainability*. MDPI AG, 12(18), p. 7403. doi: 10.3390/su12187403.

Yunsheng, Z. *et al.* (2007) 'Synthesis and heavy metal immobilization behaviors of slag based geopolymer', *Journal of Hazardous Materials*. Elsevier, 143(1–2), pp. 206–213. doi: 10.1016/j.jhazmat.2006.09.033.

Zhang, L. (2013) 'Production of bricks from waste materials - A review', *Construction and Building Materials*. Elsevier, pp. 643–655. doi: 10.1016/j.conbuildmat.2013.05.043.

Zhang, L., Ahmari, S. and Zhang, J. (2011) 'Synthesis and characterization of fly ash modified mine tailings-based geopolymers', *Construction and Building Materials*. Elsevier, 25(9), pp. 3773–3781. doi: 10.1016/j.conbuildmat.2011.04.005.

Zhang, Z. *et al.* (2018) 'A review of studies on bricks using alternative materials and approaches', *Construction and Building Materials*. Elsevier Ltd, pp. 1101–1118. doi: 10.1016/j.conbuildmat.2018.08.152.

Zuhua, Z. *et al.* (2009) 'Role of water in the synthesis of calcined kaolin-based geopolymer', *Applied Clay Science*. Elsevier, 43(2), pp. 218–223. doi: 10.1016/j.clay.2008.09.003.

## Figure captions.

Figure 1. XRD Patterns of binder materials. a) LFS, b) Fly ash and c) GGBS

Figure 2. Cumulative PSD of the binder materials.

Figure 3. Preparation of samples

Figure 4. Compressive strength of the alkali-activated samples

Figure 5. Relationships between compressive strength and $SiO_2/Al_2O_3$ molar ratio of the alkali-activated samples

Figure 6. Relationships between compressive strength and $H_2O/Na_2O$ molar ratio of the alkali-activated samples

Figure 7. Relationships between compressive strength and $Na_2O/SiO_2$ molar ratio of the alkali-activated samples

Figure 8. Water absorption of the alkali-activated bricks

Figure 9. SEM images of the binder materials. a) LFS, b) Fly ash and c) GGBS

Figure 10. SEM micrographs of the T3 paste after a) 18 hours and b) 7 days of curing