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Utilization of Co-Fired Blended Ash and Chopped Basalt Fiber in the Development of Sustainable Mortar

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Abstract: Excessive consumption of cement in construction materials has resulted in a negative impact on the environment. This leads to the need of finding an alternative binder as a sustainable construction material. Different wastes that are rich in aluminosilicates have proved to be a valuable material for alkali-activated product development, which contains zero cement. Alkali-activated products are claimed to be sustainable and cost-effective. In the present study, alkali-activated reinforced masonry mortar was developed using locally available industrial waste (co-fired blended ash—CBA). Appropriate mortar design is one of the key challenges as connections between two structural elements play a significant role in building construction. The mortar designed with suitable fiber reinforcement shall significantly help to enhance the fresh, mechanical, durability, and dynamic properties. Chopped basalt fibers (CBFs) obtained from basalt rock are one of the eco-efficient fibers applied as a reinforcing material. The present study checked the feasibility of novel industrial waste-co-fired blended ash (CBA) in the development of alkali-activated masonry mortar and reinforced alkali-activated mortar. In view of sustainable construction material design, the study elaborated the application of chopped basalt fibers (CBFs) in alkali-activated mortar design. The mortar cubes were cast and tested for various properties with varying percentages of chopped basalt fibers (0.5%, 1%, and 1.5%). The results suggest that developed mortars were able to achieve higher compressive strength (10–18 MPa) and flexural strength (3–3.5 MPa). Further, based on the properties of developed alkali-activated reinforced mortar, masonry prisms were cast and evaluated for the bond strengths (flexural and shear) of masonry. The optimum properties of alkali-activated mortar were found for the mix design of alkali activator to solid ratio of 0.40 and 0.5% CBF percentage. Application of CBF in CBA alkali-activated reinforced masonry mortar proved to be an efficient construction material with no cement.

Keywords: alkali-activated; bond strength; fibers; co-fired blended ash; waste

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1. Introduction

Over the years, migration from rural to urban areas has increased significantly due to employment and other opportunities. Due to the increasing urban population, demand for housing has also increased exponentially [1]. New infrastructure is predominantly required to enable economic development and meet basic needs such as utilities and transport networks. Building components such as foundation, floor, slab, columns, beams, and masonry require a large amount of construction materials such as concrete, steel, bricks, mortar, etc., which directly or indirectly affects the environment and economy [2,3]. Around the globe, consumption of cement for construction materials is reported as 5000 million tons in 2016, and it is forecasted to reach 6000 million tons by 2022. This creates a negative impact on the environment [4]. Cement manufacturing is an energy-intensive process and imparts a high carbon footprint due to the consumption of a large amount of fossil fuel. For every ton of cement production, about 900 kg of CO_2 is emitted, which contributes to 5–7% of total CO_2 emissions around the globe [5]. After aluminum and steel, the manufacturing of Portland cement is the most energy-demanding process as it consumes 4GJ per ton of energy. India has signed the Kyoto Protocol, which is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its parties by setting internationally binding emission reduction targets. Under this agreement, countries commit to reduce their emissions of CO_2 and five other greenhouse gases (GHGs) [6]. Therefore, the major challenge is to reduce these emissions in the cement industry and use the carbon limits in other manufacturing industries, which will help in GDP increment and national development.

To reduce the demand for cement in the construction industry, it is desired to design and develop a sustainable binder. This can be done by the process called alkali activation that involves activation of raw materials consisting of alumina and silica, which produces alumino-silicate gel and hardens to obtain the desired construction materials. As an alternative solution, sustainable construction materials developed by the alkali activation of aluminosilicates with lesser environmental impact and desired properties were investigated by many researchers [7,8]. In addition, the continuous surge in waste generation created a challenge for the researchers to propose solutions for its reuse. The advantage of alkali-activated mortar over conventional masonry mortar is that it uses raw materials that help to reduce the stocks of solid wastes. Masonry is one of the important parts of a building that consists of a masonry unit, which is joined and finished by mortar. Alkali-activated mortar is advantageous over conventional cement or lime mortar as it gains high early strength and is more durable and environmentally friendly [9]. Various researchers have developed alkali-activated mortars from different industrial wastes such as fly ash (FA), rice husk ash (RHA), bottom ashes, boiler ashes, ground granulated blast furnace slag (GGBS), mine wastes, metal industries, and kaolin which were activated by alkaline hydroxides and silicates (Table 1). Previous studies stated that ashes with high silica and alumina content are feasible to produce alkali-activated products (geopolymer) [10]. Application of alkali-activated mortar in masonry construction enhances the structural performance of buildings [11,12]. These materials, which are the major source of aluminum and silicates, react in a hydrothermal alkaline environment (hydroxides and silicates of alkalis), resulting in rock-like hard structures. They consist of a polymeric framework of silica-oxygen-aluminum (Si-O-Al) with alternate sharing of four oxygen atoms as SiO_4 and AlO_4. The four-coordinated oxygen of aluminum (Al) imparts free negative charge, which should be balanced with positive ions to have a stable matrix [13,14]. These essential cations are calcium (Ca_2+), sodium (Na+), potassium (K+) ions, etc.

The properties of masonry mortar depend on the characterization of raw materials along with the liquid to solid ratio, modulus ratio, and concentration of alkali hydroxide. From the studied literature, the workable ranges of the liquid to solid ratio, concentration of sodium hydroxide, and Na_2SiO_3/NaOH were found to be 0.4–2.5, 6 M to 16 M, and 1–2.5, respectively (Table 1). In addition, age and curing temperature play a vital role in the mechanical properties of mortar. Sata et al. [15] found that the compressive strength of bottom ash-based geopolymer mortar was improved with increasing fineness of ash. Moreover, the activators shall be used as per the properties of raw materials. It is possible to achieve compressive strengths of 5 MPa to almost 45 MPa at the age of 28 days for the various molar concentrations of alkali activators [16]. However, a higher concentration of alkali hydroxide reduces the strength of mortar as it breaks the Si-Al bonding [17]. Furthermore, it increases the total construction cost of masonry. Researchers have also shown that the addition of the GGBS enhances the setting, strength gain, and durability of a mortar [18]. Hence, to obtain desired properties, blending of two or more siliceous materials is designed.

Table 1. Raw materials used for alkali-activated masonry mortar.

Source Material (SM)	Particle Size	Alkali Activator (AA)	AA to SM Proportion (By wt.)	Reference
Lignite bottom ash	120 µm	NaOH (10 M) and sodium silicate in the ratio of 1:1	0.56	[15]
Rice husk ash (RHA)	25.42 µm	NaOH (7–10 M) and sodium silicate in the ratio of 2.5:1	2.50	[16]
Fly ash with silica fume	1–100 µm	NaOH (8 M) and sodium silicate in the ratio of 1:1	0.54	[19]
Ground granulated blast furnace slag and low-calcium fly ash	30 µm	NaOH (8 M) and sodium silicate in the ratio of 2:1	0.40	[20]
Palm oil fuel ash	22.78 µm	NaOH (16 M) and sodium silicate in the ratio of 2.5:1	0.50	[21]
Red mud (alumina refinery waste) with RHA	5–300 µm	NaOH (4 M) and de-ionized water	1.20	[22]
Bottom ash with FA	Fineness modulus of 0.14	KOH (6–14 M) and potassium silicate in the ratio of 1:1	0.4	[23]

Mortar is a binding material that glues individual units (bricks or blocks) together and seals the building against moisture and air penetration. Even though mortar shares only 7% of the total masonry wall volume, it plays a crucial role in the structural performance [24]. The inclusion of fibers in mortar plays a vital role in strengthening. A number of researchers have evaluated the properties of basalt fiber-reinforced mortars and concrete. Several comparative studies of reinforced mortar with basalt fiber (treated/untreated, chopped/long, etc.) and other natural (banana, coconut, sisal) and artificial fiber (carbon, glass, steel, polyvinyl alcohol, polyethylene) were carried out by various researchers [25–28]. Preferred dimensions of basalt fibers for improved performance were observed to be in the range of about 8 to 14 µm (microns) in diameter and 3 to 6 mm in length. For reinforced mortar, fibers shall be in the proportional range of 0.1–1.5% that gives better mechanical strength and durability [29]. Ralegaonkar et al. [28] studied the effect of chopped and long basalt fibers in reinforced cement mortar. The study concluded that 1% of long fibers is the optimum percentage for reinforced cement mortar. Fenu et al. [25] found that basalt fibers are suitable to be used in acidic as well as alkaline matrix, unlike glass fibers. This is the reason researchers have chosen basalt fibers for reinforcing geopolymer concrete [30,31]. Although several studies were carried out on basalt fiber reinforced mortar, investigation of reinforcing chopped basalt fibers in alkali-activated mortar is limited. Celik et al. [32] found that basalt fiber mortar shows maximum flexural strength at 1.2% basalt fibers with 12 M NaOH concentration. A similar increase in flexural strength of mortar by 10% to 20% was found at 12 M NaOH concentration by using metakaolin and slag as a source material [33]. Ali et al. [34] studied the combination of basalt fiber with metakaolin alkali-activated mortar, for a Na_2SiO_3 to NaOH ratio of two. Guo et al. [35] found better results with basalt fiber in combination with fly ash and steel slag-based alkali-activated mortar for a constant sand to binder ratio of 2.5. Although studies were carried out for designing mortar using ash, alkali activator, and basalt fiber, there is very limited work on the application of locally available co-fired ash with a lower concentration of alkali activators.

The present paper deals with the study of alkali-activated mortar design using blended ash, which was obtained from co-combustion of rice husk and coal in 80:20 (by weight), with sodium-based alkali activators. It also investigates the application of basalt fiber in reinforced alkali-activated mortar. The ratio of Na_2SiO_3 to NaOH was kept as a unity, and the molar concentration of NaOH was 8 M. From the literature, it was inferred that less energy is required to produce basalt fiber and that it is obtained from naturally available basalt rock [36]. Besides this, chopped basalt fiber (CBF) has a lower impact on human beings and minimal toxic effects [37]. These fibers are non-reactive in saline water, acidic environment, and alkaline system. They are non-reactive with chemicals either, thus making them more suitable to be used with geopolymeric solution [38]. The present study also examined the use of chopped basalt fiber in an alkali-activated composite for masonry application. This experimental study evaluated the rheological, mechanical, and durability properties of reinforced alkali-activated masonry mortar in comparison with the unreinforced mortar.

2. Materials and Methodology

To design and develop an optimum mix of masonry mortar, residual ash obtained from the co-combustion of biomasses in the industrial boiler was used as a source material. The locally available co-fired blended ash (CBA) was procured from Malu Paper Mills, located in Nagpur, Maharashtra, India, which was further activated by commercially available alkali hydroxide and silicate, viz. sodium hydroxide, i.e., NaOH (SH) and liquid sodium silicate (LSS) with an SH (8 M) to LSS ratio of 1: 1 (by weight). In addition to the source material and alkali activators, natural sand of Zone II [39] was used as a filler material in the preparation of masonry mortar. Further, the chopped basalt fiber (CBF) with 12 mm in length and 13 μm in diameter was used for the strengthening of alkali-activated masonry mortar.

2.1. Characterisation of Raw Materials

The raw materials used in the study were co-fired blended ash (CBA), natural sand, alkali activators (NaOH and Na_2SiO_3), and additional potable water to maintain the flow of masonry mortar. CBA consists of coal and rice husk in the proportion of 20:80 by weight. The source material was analyzed for its physical, chemical, mineralogical, and morphological properties to evaluate its feasibility as a raw material for sustainable construction material. For this, physical properties (particle size distribution, specific gravity, and bulk density), mineralogical (X-ray diffraction (XRD)), and morphological (Scanning electron microscope (SEM)) characterization of the material was performed. Next, X-ray fluorescence (XRF) and loss on ignition (LOI) were carried out to find its chemical behavior. In addition, to check the thermal stability of ash, thermogravimetric (TgDTG) analysis was carried out. Figure 1 shows the photograph of CBA, which is black-colored (mean particle size—100 μm; specific gravity—2.29; bulk density—1430 kg/m^3).

Figure 1. Co-fired blended ash (CBA) sample procured from a paper mill company.

To synthesize aluminosilicates, an alkaline medium is required. A sodium-based alkali activator was used for the study of masonry mortar development. It consists of NaOH (molar concentration—8 M) and liquid sodium silicate (37% Wt. percentage (28% silica + 9% sodium oxide) and water 63% having pH of 11.3). The resultant product of a geopolymeric reaction has the polymeric framework of silica-oxygen-aluminum (Si-O-Al) with alternate sharing of four oxygen atoms as SiO_4 and AlO_4 that leads to geopolymeric gel formation followed by setting and hardening at an ambient curing condition. The alkali activator was produced by adding NaOH pellets in water as desired and LSS in 1:1 proportion, which was then kept for cooling before using it for mortar mixing. Chopped basalt fiber was used for reinforcing masonry mortar. Figure 2 presents the photograph of basalt fibers used for the study.

Figure 2. Chopped basalt fiber (CBF) used for reinforcement.

2.2. Mixing and Proportioning

For the preparation of mortar, the ash was sieved using a 150 μm sieve to obtain the mean particle size of 100 μm. The volumetric analysis was performed to determine the specific gravity of ash [40] and resulted in 2.29. The natural sand of 2.63 specific gravity was used as a filler material that conforms to Zone II as per IS 383: 1970 [39]. The proportion of NaOH (molar concentration—8 M) to LSS was taken as 1:1 (by weight percentage) with a varying liquid to solids ratio (0.3, 0.4, and 0.5). As per IS 2250: 1981 [41], to maintain the flow of masonry mortar as 110, desired water was added in the dry mix (Figure 3).

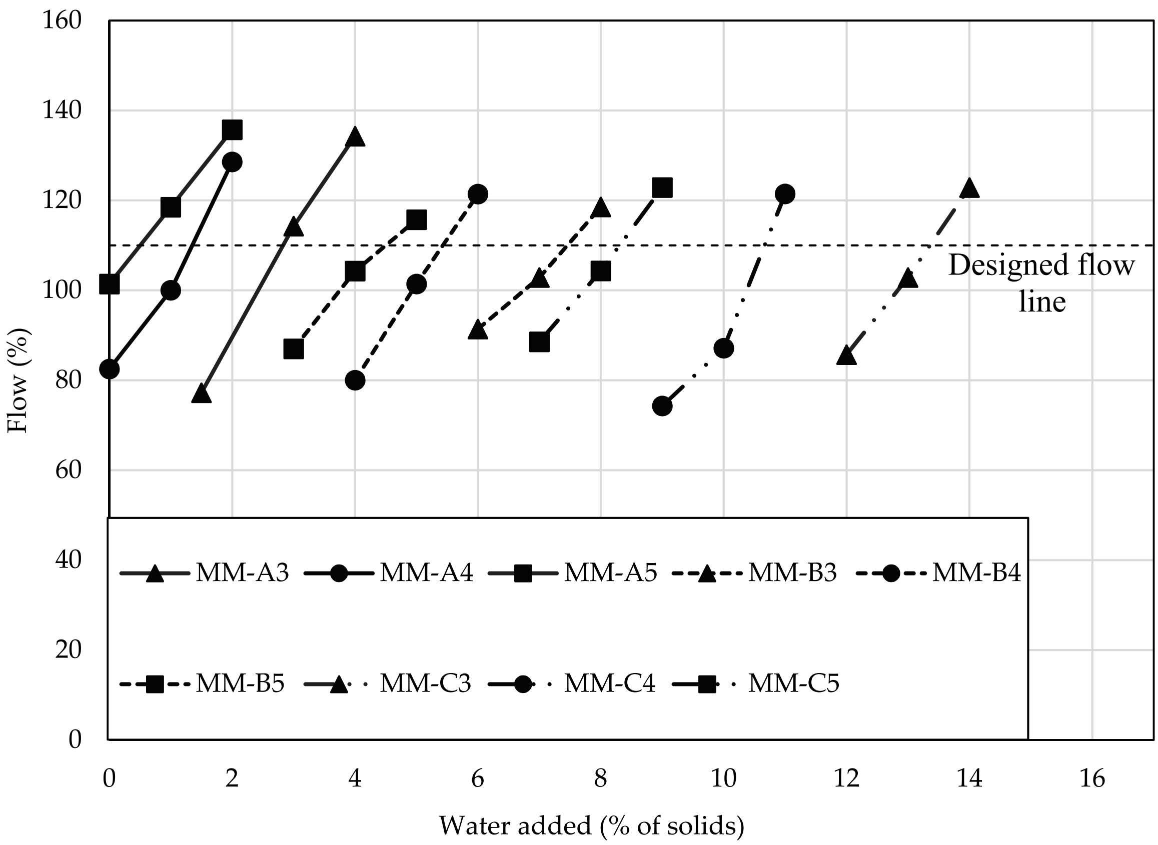


Figure 3. Additional water requirement for attaining desired flow.

Various trials with altering the ash to sand ratio were carried out as 1:1, 1.5:1, and 2:1. The obtained mix with the increase in ash proportion beyond 2:1 was not sound. Hence, trials were limited to the aforesaid proportions. Table 2 presents the design matrix of the performed experimental work. Designed mixes were categorized using the nomenclature as MM for mortar mix. Notations A, B, and C represent the variation of the ash to sand ratio as 1:1, 1.5:1, and 2:1, respectively, and the numbers 3, 4, and 5 represent the variation of the alkali activator to solid ratio as 0.3, 0.4, and 0.5, respectively. For example, in A4, A represents mortar with one part of ash and one part of sand (ash: sand—1:1), while 4 represents the alkali activator to solid ratio as 0.4.

Table 2. Design matrix of considered mix proportions.

Design Mix	Blended Ash to Sand Ratio	Alkali Activator (NaOH (8 M): Na_2SiO_3) :: 1:1 to Solid Ratio
MM-A3	1:1	0.3
MM-A4	1:1	0.4
MM-A5	1:1	0.5
MM-B3	1.5:1	0.3
MM-B4	1.5:1	0.4
MM-B5	1.5:1	0.5
MM-C3	2:1	0.3
MM-C4	2:1	0.4
MM-C5	2:1	0.5

The constituents of masonry mortar CBA, sand, water, and alkali activator were mixed in various proportions with an alteration of basalt fiber percentages in it. Dry mixes were prepared with CBA and sand in the ratios of 1:1, 1.5:1, and 2:1 (by weight). CBF was added as reinforcement in varying proportions (0.5%, 1%, and 1.5% of the total dry mix). The alkali activator was prepared by mixing NaOH (8 M) and liquid sodium silicate (commercial grade) in 1:1 proportion and used after a few hours. The mortar ingredients were mixed in a laboratory mortar mixer. A dry mix of CBA and sand was mixed for one minute. The solution of sodium hydroxide and liquid sodium silicate was added to the dry mix. Continuous mixing was done in order to achieve a homogenous mix. The developed mortar was then checked for its practical application by checking its flow value. To achieve the desired flow, additional water was added as per the requirement of IS 2250: 1981 [41]. Table 3 presents the mix proportions considered with varying basalt fiber for various trials. MM-A, MM-B, and MM-C represent mortar mixes of CBA and sand in the ratio of 1:1, 1.5:1, and 2:1, respectively, and 0.5, 1, and 1.5 in the abbreviation of the design mix represent the variation of fiber percentage as 0.5%, 1%, and 1.5% by weight of dry mix. The water required by percentage of the weight of solids in the mix to achieve the desired flow for fiber-reinforced mortar is shown in Figure 4.

Table 3. Design matrix for reinforced masonry mortar.

Design Mix	Blended Ash to Sand Ratio	Alkali Activator (NaOH (8 M): Na_2SiO_3) :: 1:1 to Solid Ratio	Fiber % (by Weight of Dry Mix)
MM-A4	1:1	0.4	0
MM-A4-0.5	1:1	0.4	0.5
MM-A4-1	1:1	0.4	1.0
MM-A4-1.5	1:1	0.4	1.5
MM-B4	1.5:1	0.4	0
MM-B4-0.5	1.5:1	0.4	0.5
MM-B4-1	1.5:1	0.4	1
MM-B4-1.5	1.5:1	0.4	1.5
MM-C4	2:1	0.4	0
MM-C4-0.5	2:1	0.4	0.5
MM-C4-1	2:1	0.4	1
MM-C4-1.5	2:1	0.4	1.5

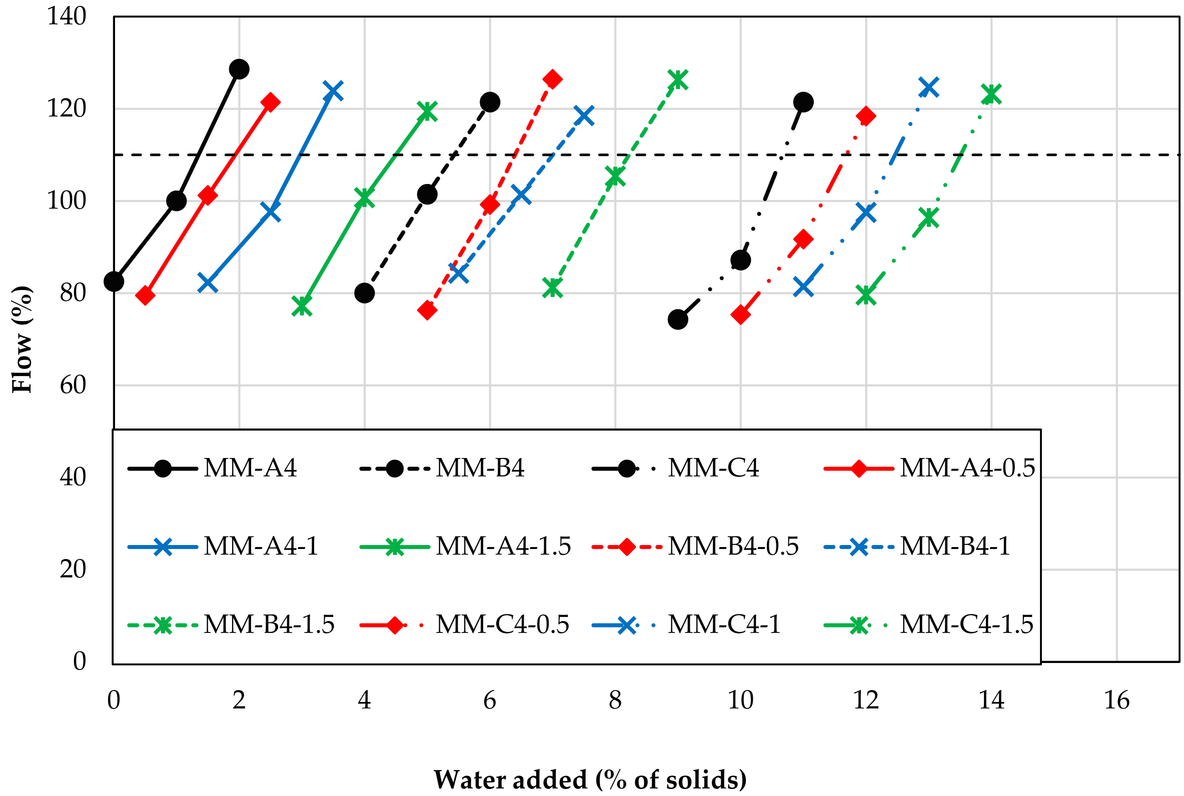


Figure 4. Flow value.

2.3. Performance Evaluation

In order to evaluate the suitability of raw materials, i.e., blended ash and sand for masonry mortar, physical and chemical characterization was carried out. The standard procedure followed to evaluate the characteristics of CBA is presented in Table 4.

Table 4. Standard test procedures for material characterization.

Properties	Standard Procedure
Particle size distribution	Sieve analysis [40]
Specific gravity	Volume displacement [40]
Chemical composition and loss on ignition (LOI)	X-ray fluorescence (XRF) spectrometry using PANalytical PW2403 MagiX
Mineralogy	X-ray diffraction (XRD) analysis using PANalytical X'Pert Pro X-Ray diffraction
Morphology	Scanning electron microscopic (SEM) analysis—Carbon-coated sample particles were used for capturing the microscope images by the backscattering of the electrons at 5 kV in vacuum condition
Thermal stability	Thermogravimetry (TG) test using diamond TG, PerkinElmer

The flow value of masonry mortar was determined by the flow table test that gives the workability of mortar. The air content of masonry mortar depicts the air voids present in it. ASTM C185, 2015, gives a detailed procedure for the evaluation of air content of mortar [42]. The mortar mix was prepared and placed in the mold of a flow table. The flow table was raised up and allowed to fall 25 times in 15 s. The desired flow was maintained by adding an extra amount of water, and it was freshly placed in a known volume (400 mL) container. The container was weighed for determining the air content of masonry mortar. Knowing the density of mortar and its constituents along with the quantities of material, the air content of mortar was evaluated. Figure 5 shows the experimental setup of the flow table test.

Figure 5. Flow table test.

Various mix designs with optimum alkali activator solution were prepared until the specified flow was achieved. The air content was determined by calculating the measured density of mortar, known densities of ingredients, and mix proportions [42].

Indian Standard IS 2250: 1981 gives the specification and procedure to carry out the compressive strength of mortar [41]. Specimens of size 50 mm × 50 mm × 50 mm were cast for the compressive strength test. The specimen was demolded after 24 h of casting and tested for compressive strength at the age of 7 days, 14 days, and 28 days. ASTM C78, 2002, states the procedure for the flexure strength of mortar [43]. Lipatov et al. [37] with reference to Russian Standard GOST 30,744 [44] stated the flexure strength of mortar could be done with 3-point bending on a 40 mm × 40 mm × 160 mm beam (Figure 6).

Figure 6. Flexural strength of mortar.

The test was performed on a multifunctional control console machine-8 (MCC-8). The load was applied by displacement control with a rate of 0.2 mm/min until the specimen failed. The modulus of rupture was calculated by equation (1), where R, P, L, b, and d denote the modulus of rupture, load at failure, and the span, breadth, and depth of a beam, respectively.

$$R = (3PL)/(2bd^2) \quad (1)$$

The flexural bond strength of masonry was evaluated by the procedure given in the Standard (ASTM E518, 2015) [45]. The bricks used for all types of design mixes were the fly ash bricks having the dimension and strength of 0.19 × 0.09 × 0.09 m^3 and 6.5 MPa, respectively, and were used for all the tests performed for mortar. Test results were obtained and compared for non-reinforced and reinforced masonry mortar. The test was carried out with the five bricks prism, where the mortar thickness of 10 ± 1.5 mm was applied for interface bonding (Figure 7).

Figure 7. Flexural bond strength of mortar.

IS 456: 2000 recommends chloride and sulfate content limits in the mortar in order to protect the embedded steel as well as deterioration due to expansion and disruption of mortar [46]. The chloride concentration was evaluated on the water-soluble extraction of product as per IS 3025: 1988 (Part 32) [47]. Similarly, the sulfate concentration was also determined as per IS 3025: 2003 (Part 24) [48].

3. Results and Discussion

The mineralogical (Figure 8) and morphological characteristics (Figure 9) of ash were evaluated by XRD and SEM analysis. The XRD of CBA depicts an amorphous nature of ash that enhances the reaction and imparts good strength (Figure 8). The sharp peak shows the silica present in the form of quartz, which is crystalline. Other broad and diffused humps represent an amorphous nature of the ash. Moreover, after the alkali activation process, peak shifts to the right side, i.e., 2Θvalue will increase due to the formation of aluminosilicate gel [49]. Figure 9 shows the morphology of raw materials that depicts the porous nature of CBA. The ash was examined for chemical composition, which was carried out by XRF (Table 5). The blended ash contains silica, alumina, and iron, having 68.5 + 3.39 + 8.89 = 80.78% of SiO_2 + Fe_2O_3 + Al_2O_3 (percentage) and 9.7% LOI. This indicates the identified ash has the potential to be used for alkali activation. In addition, loss on ignition (LOI) was obtained through thermogravimetric (TgDTG) analysis (Figure 10) where, DTG and DSC is derivative thermogravimetry and differential scanning calorimetry respectively. The mass drops of 3.19% (250 °C) and 5.83% (750 °C) were observed due to the evaporation of water present in the ash sample. The last drop of 0.67% resulted due to the decomposition of carbonaceous matter and impurities present. In addition to the source material, well-graded river sand (Table 6) and the chopped basalt fibers were used (Table 7).

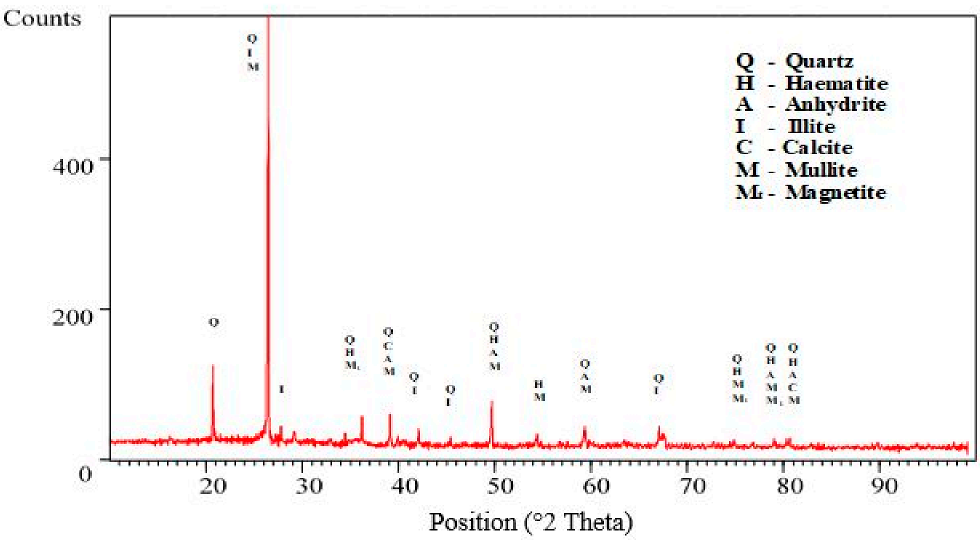


Figure 8. Mineralogical phases present in CBA.

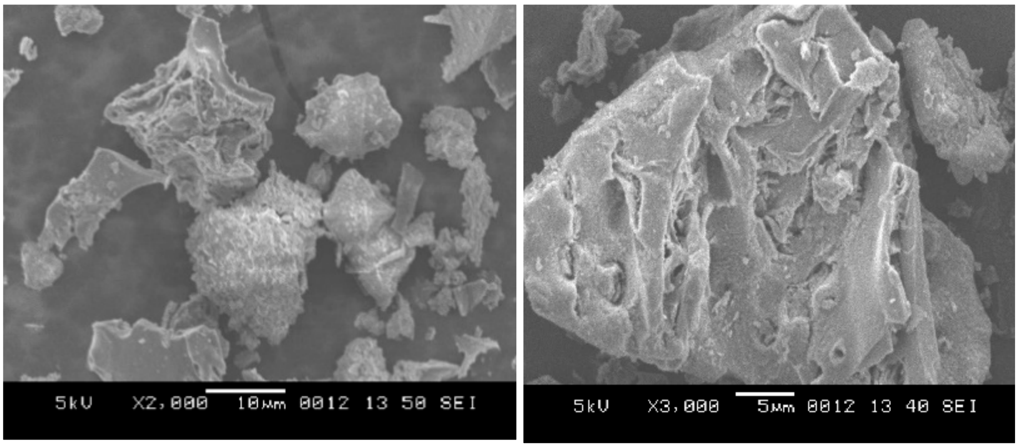


Figure 9. SEM analysis of CBA.

Table 5. XRF scan of CBA sample.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	K_2O	SO_3	CaO	TiO_2	MgO	P_2O_5	Na_2O
(%)	68.50	8.89	3.39	1.68	1.42	1.40	0.68	0.56	0.53	0.16

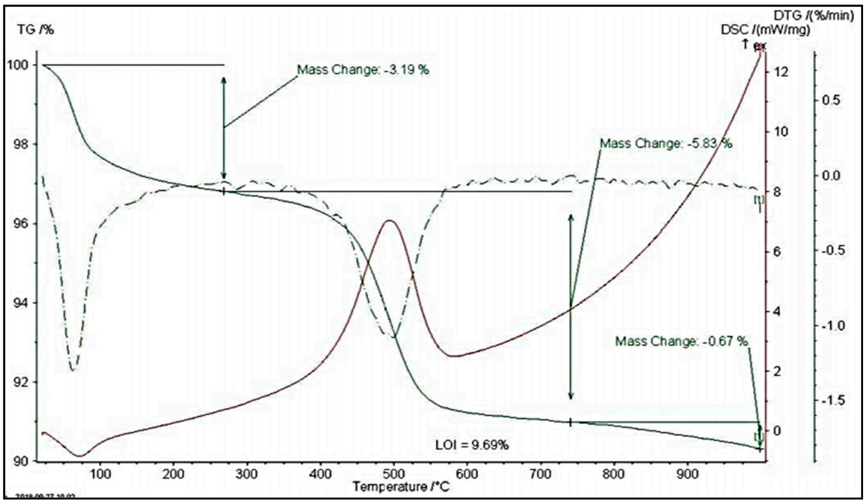


Figure 10. Thermogravimetric analysis of CBA.

Table 6. Physical characteristics of raw materials used for masonry mortar.

Physical Properties	Standard	CBA	Physical Properties	Standard	Sand
Mean particle size (μm)	IS 1727-1967	100	Mean particle size (μm)	IS 2386-Part 1—1963 [50]	150
Specific gravity	IS 1727-1967	2.29	Specific gravity	IS 2386-Part 3—1963 [51]	2.63
Bulk density (g/cc)	IS 1727-1967	1.43	Bulk density (g/cc)	IS 2386-Part 3—1963 [51]	1.76
Color	-	Black	Color	-	Brown

Table 7. Physical and mechanical properties of basalt fibers.

Property	Value
Density (kg/m^3)	2630
Tensile strength (MPa)	3200–3850
Elastic modulus (GPa)	75–90
Elongation at break (%)	3.1
Softening point (°C)	1050
Working temperature (°C)	−260 to 650
Thermal conductivity (W/m.K)	0.030–0.036
Electrical resistance (Ohm.m)	1×10^{12}
Acoustical normal coefficient of sound absorption	0.9–0.99

The masonry mortar mixes were further analyzed for the determination of air content [42]. The resulted range of evaluated air content for the analyzed mortar mixes was found to comply with ASTM C185, 2015. It was observed that with the increase in ash content, the air content also increases (Table 8) due to its porous nature and bumpy surface (Figure 9).

Table 8. Air content of masonry mortars.

Mortar Mix	Air Content (%)	Mortar Mix	Air Content (%)	Mortar Mix	Air Content (%)
MM-A3	13.51	MM-B3	17.43	MM-C3	18.53
MM-A4	11.20	MM-B4	15.08	MM-C4	17.44
MM-A5	12.52	MM-B5	16.22	MM-C5	18.28

The compressive strength of masonry mortar samples for various mix proportions at the age of 7, 14, and 28 days were obtained (Figure 11). Like cementitious materials, the compressive strength of alkali-activated mortar increases with an increase in age. With respect to 28 days compressive strength, developed masonry mortar achieved almost 45%, 50%, and 55% strength at the age of seven days for the ash to sand ratio of 1:1, 1.5:1, and 2:1, respectively. The results indicate that as the content of ash increased, the percentage gain in early strength also increased. However, the later strength (28 days) of masonry mortar was estimated as highest for 1:1 and lowest for 2:1 proportion of CBA and sand. With the increase in CBA content, the surface area also increased, which led to an increase in the alkali-activated solution absorption affecting the dissolution of aluminosilicates and resulting in comparatively lower strength.

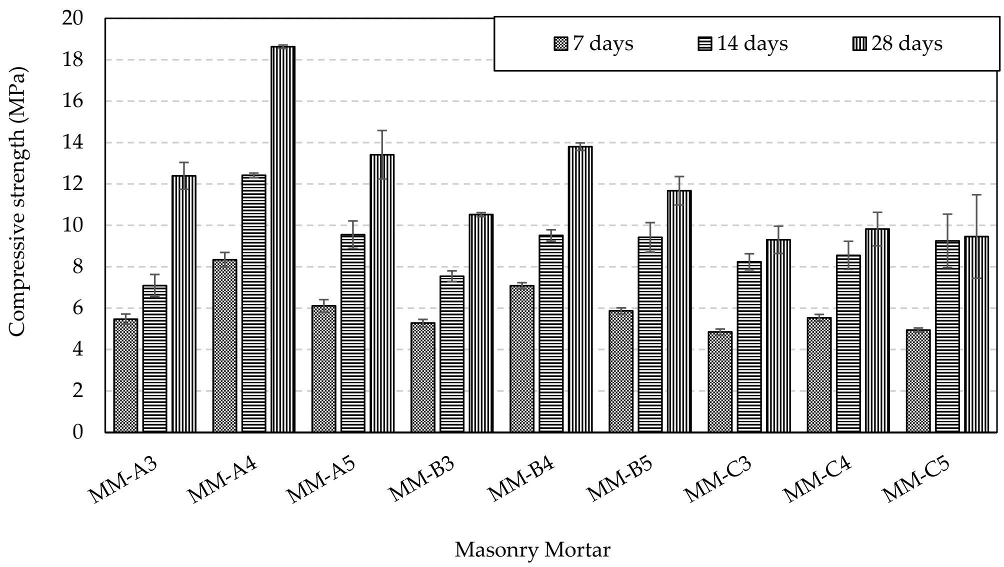
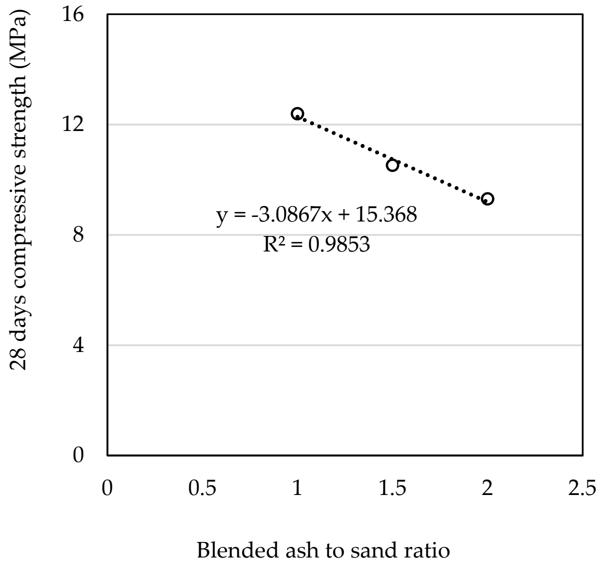
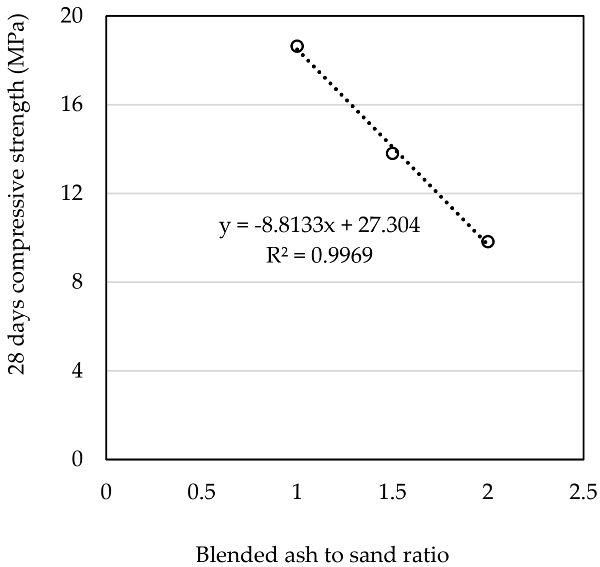


Figure 11. Compressive strength (MPa) of masonry mortar at the age of 7, 14, and 28 days.

The compressive strength increases as the alkali activator (AA)/solid ratio increases from 0.3 to 0.4, but the further increment to 0.5 decreases the compressive strength. This is due to the lower content of the alkali activator not being enough to leach the amorphous aluminum silicates from the blended ash for the alkali activation process. On the other hand, a higher liquid to solid ratio produces a larger amount of hydroxide ions than the required for alkali activation reaction. This reduces the strength of masonry mortar [52]. The trend of 28 days strength for different alkali activator to solid ratios with the variation of ash proportions is shown in Figure 12a–c. It indicates the negative trend for compressive strength when compared with the ash to sand ratio. From Figure 13, it is inferred that the compressive strength of masonry mortar decreases with the increase in air content.

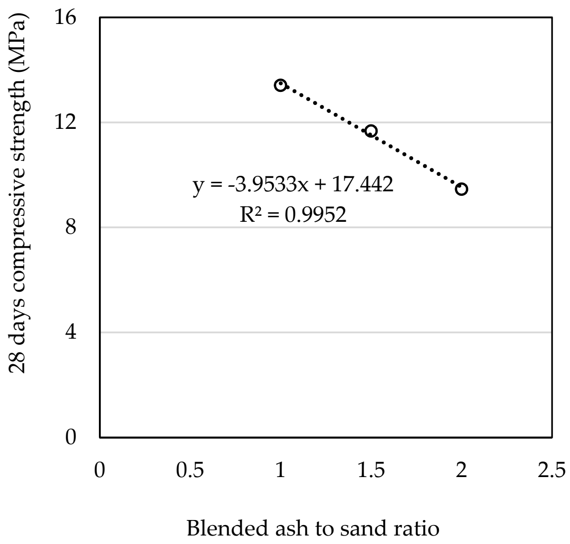


(**a**) AA/Solid ratio—0.30



(**b**) AA/Solid ratio—0.40

Figure 12. *Cont.*



(**c**) AA/Solid ratio—0.50

Figure 12. Trend of 28 days compressive strength with variation in the blended ash to sand proportions.

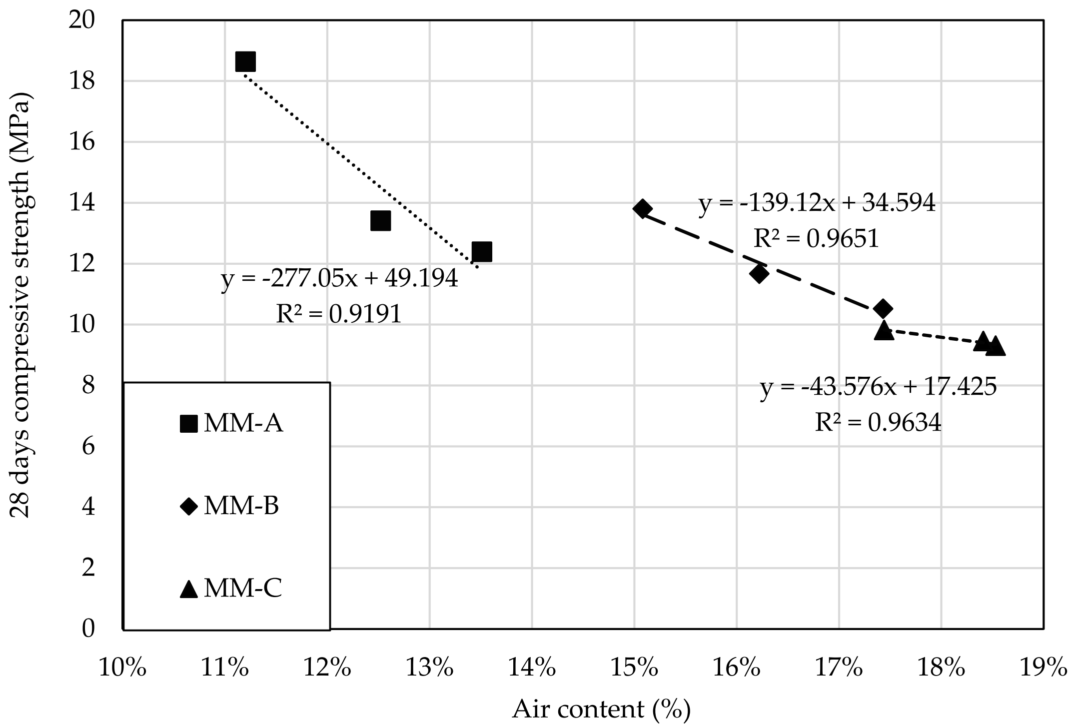


Figure 13. Relation between air content and compressive strength of masonry mortars.

The flexural strength of masonry mortars at the age of 28 days was determined. It was observed that there was no significant variation in the obtained results. Figure 14 presents the variation in flexural strength of various mixes of masonry mortar. MM-3, MM-4, and MM-5 indicate a masonry mortar mix with an AA to solids ratio of 0.3, 0.4, and 0.5, respectively. Meanwhile, MM-A, MM-B, and MM-C represent mortar mixes of blended ash and sand in the ratio of 1:1, 1.5:1, and 2:1, respectively. It was clearly observed that mortar with high ash content possesses lesser flexural strength, which is similar to the compressive strength trend.

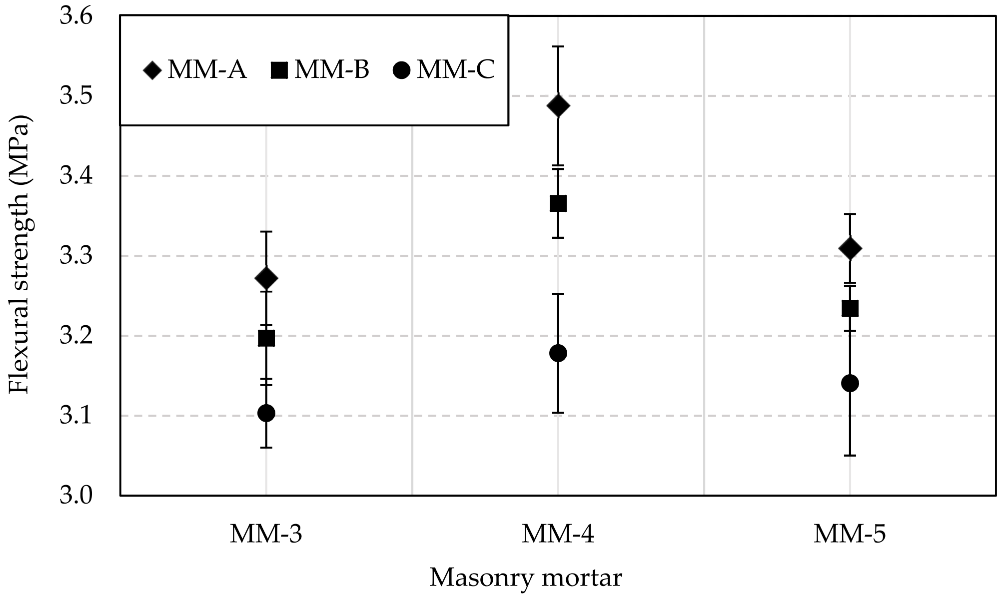


Figure 14. Flexural strength (MPa) of masonry mortar at the age of 28 days.

Further, mix designs with a 0.4 alkali activator to dry mix ratio were selected for investigating the effect of CBF in it by experimentation. Addition of fibers (0.5%, 1%, and 1.5%) reduced the compressive strength by around 23%, 40%, and 50% for the ash to sand ratio of 1:1; 23%, 33%, and 50% for the 1.5:1 ash to sand ratio and 18%, 27%, and 50% for the ash to sand ratio of 2:1, respectively (Figure 15). From the analysis, it is observed that, with the increase in fiber content, there is an exponential reduction in strength.

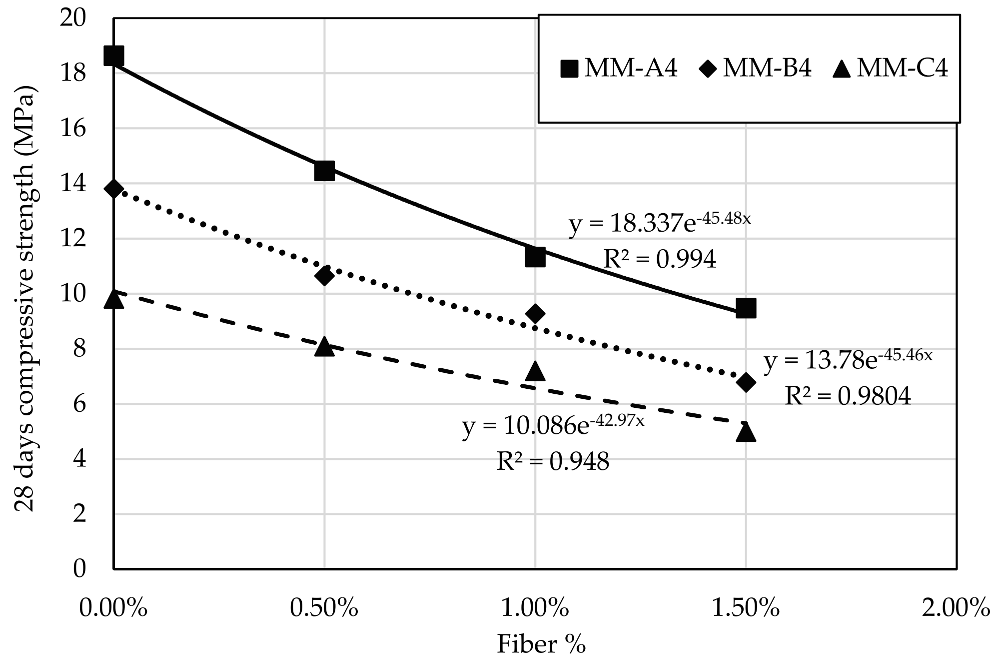
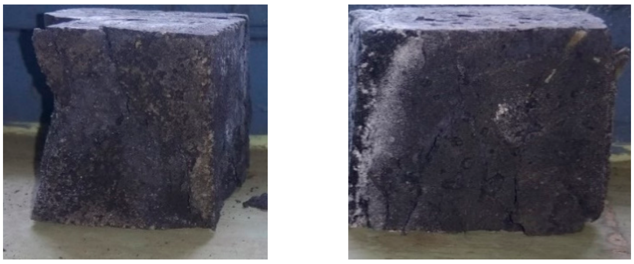


Figure 15. Compressive strength of reinforced masonry mortar.

An increase in the percentage of fibers results in increased air content that gives lower compressive strength as compared to unreinforced mortar. However, the failure pattern of the blocks was depicted by the cracks present on the surface (Figure 16a,b). It did not leave the material apart, unlike unreinforced mortar blocks, which indicates the homogeneity and holding property of fiber that shall reduce the structural damage.



(**a**) Unreinforced masonry mortar (**b**) Fiber-reinforced mortar

Figure 16. Failure pattern after compressive strength test.

Although there was a reduction in compressive strength with the increase in fiber percentage, flexural strength and flexural bond strength of reinforced masonry mortars were observed to be higher than the unreinforced mortar. Masonry is one of the primary structures, and it plays a vital role in reinforced concrete (RC)-framed structure. It is weak in tension and has a low ductility response. For strengthening the brick masonry, it is essential to increase the strength of masonry mortar. Masonry walls subjected to lateral load should possess high flexural bond strength to avoid failure. Figure 17 shows the flexure strength variation of plain and fiber-reinforced alkali-activated mortar. It was observed that for the variation of fiber from 0.5% to 1.5%, there was an increase in flexural strength. For the ash to sand ratio of 1:1, 1.5:1, and 2:1, as the percentage of fiber increased (0.5%, 1%, and 1.5%), the flexure strength also got increased by 12%, 14%, and 17%, 11%, 13%, and 15%, and 12%, 16%, and 17%, respectively, as compared to unreinforced alkali-activated masonry mortar.

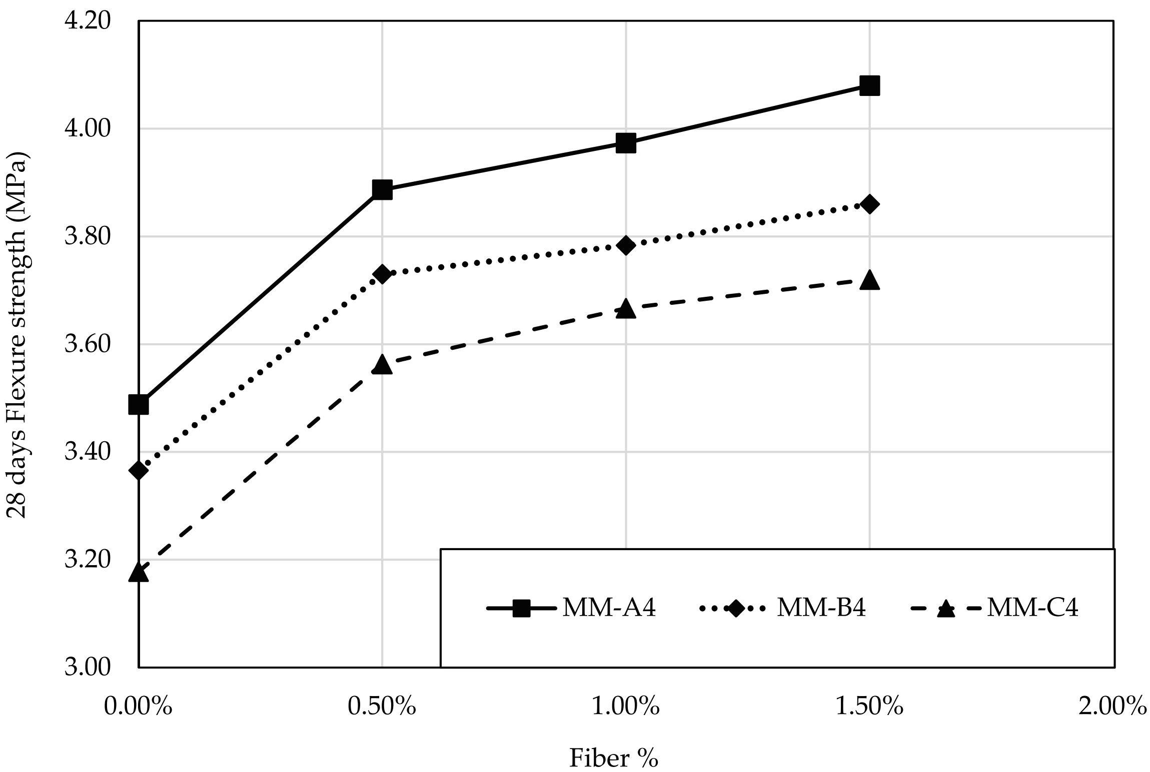


Figure 17. Flexural strength of masonry mortar at the age of 28 days.

Application of fiber into the design mix resulted in a rise of 6–14% in the flexure bond strength (Figure 18). After mixing the fiber to the proportion of 0.5%, 1%, and 1.5% of dry mix, there was an increase in the flexural bond strength by 9%, 6%, and 7%, 12%, 9%, and 9%, and 14%, 11%, and 11% of MM-A4, MM-B4, and MM-C4, respectively.

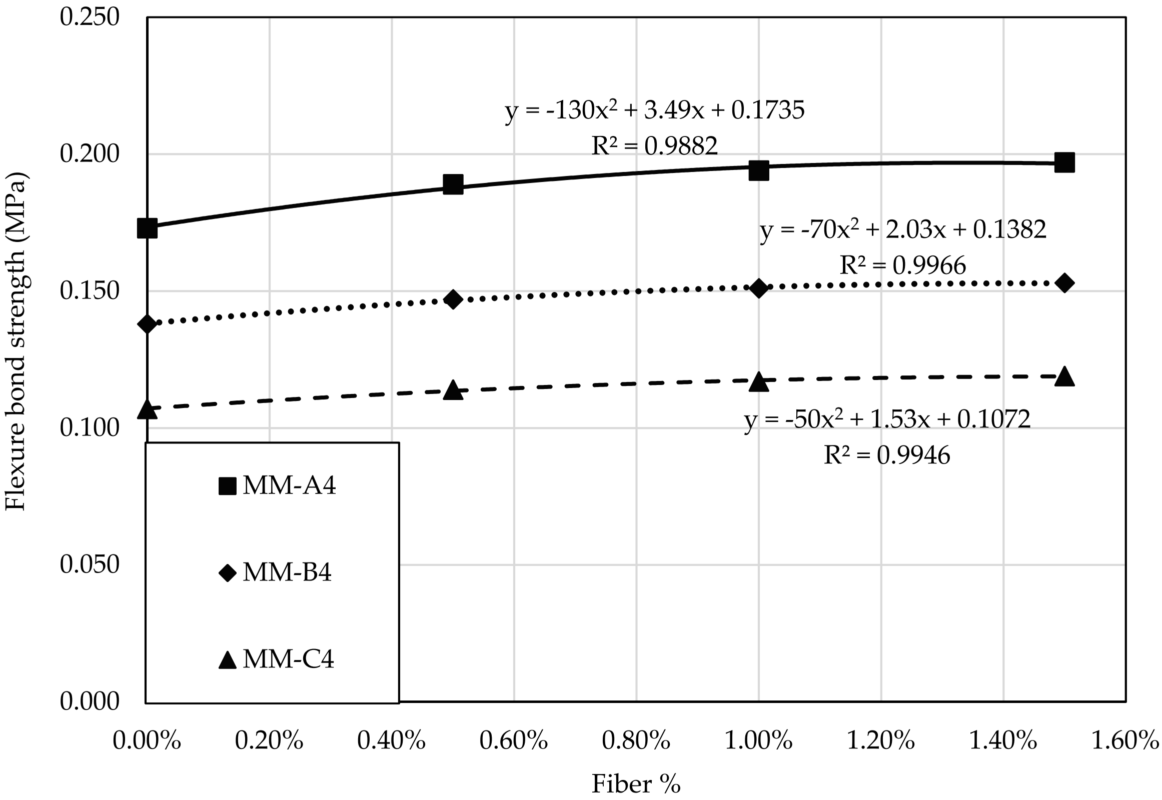


Figure 18. Flexural bond strength of reinforced and unreinforced masonry mortar (28 days).

Although a high percentage of CBF performs better for flexural stresses, there was a significant reduction in compressive strength. The mortar with a fiber content of 0.5% showed significant improvement in flexural strength compared to 0% fiber content. Further, an increase in fiber content by 1% and 1.5% showed a slight improvement compared to 0.5%. However, the reduction in compressive strength was significant in 1% and 1.5%. Hence, the percentage of 0.5% CBF was found to be the optimum proportion to achieve the desired properties of alkali-activated masonry mortar.

Careful selection of the mix and materials is necessary so that deleterious constituents do not exceed the limits. Samples with an alkali activator to mix ratio of 0.4% and 0.5% CBF for all mixes 1:1, 1.5:1, and 2:1 (ash: sand) were evaluated for sulfate and chloride content in order to check its durability. The chloride and sulfate contents of crushed samples—MM-A4-0.5, MM-B4-0.5, and MM-C4-0.5—were observed to be 198, 232.1, and 258.4 mg/L and 74, 103.6, and 150.14 mg/L, respectively. The above-mentioned values for chloride and sulfate content in the analyzed design mix were found within the prescribed limits (IS 456: 2000).

4. Conclusions

To reduce the consumption of cement, the alternate binder design using an alkali activation process was investigated. Different waste materials, which are rich in aluminosilicates, proved to be a valuable material for alkali-activated mortar development. The experimental study was carried out to obtain the optimum mix design for sustainable alkali-activated masonry mortar by varying the alkali activator to dry mix and ash to sand ratios. As the ash content increased, the mechanical strength of masonry mortar was reduced. The higher amount of ash resulted in comparatively lower strength but gained faster strength for all the cases. From various trials, samples with a 0.4 alkali activator to solid ratio were found to be the optimum mix design. Masonry mortars: MM-A4, MM-B4, and MM-C4 were recommended mix designs, which have 28 days compressive strength of around 18 MPa, 14 MPa, and 10 MPa, respectively. The present study concluded that the application of co-fired blended ash in sodium-based alkali-activated masonry mortar is a feasible and sustainable solution. It is also concluded that incorporation of 0.5% CBF is suitable for reinforcing alkali-activated masonry mortar. Moreover, CBF has high resistance to aggressive chemicals and alkali attack. Hence, the inclusion of basalt fibers for reinforcing alkali-activated mortar provides a significant solution for durable mortar. Improved performance of the CBF reinforced mortar with various raw material compositions signifies its potential use for the application and standardization for the reinforced mortar design process.

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