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Strength and durability characteristics of bricks made using coal bottom and coal fly ash

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Abstract. The study evaluates properties of brick having coal ash and explores the possibility of utilization of coal bottom ash and coal fly ash as an alternative raw material in the production of coal ash bricks. Lower cement content was used in the investigations to attain appropriate strength and prohibit high carbon content that is cause of environmental pollution. The samples use up to 7% of cement whereas sand was replaced with bottom ash. Bricks were tested for compressive strength, modulus of rupture, ultrasonic pulse velocity (UPV), water absorption and durability. The results showed mix proportions of bottom ash, fly ash and cement as 1:1:0.15 i.e., M-15 achieved optimum values. The coal ash bricks were well bonded with mortar and could be feasible alternative to conventional bricks thus can contribute towards sustainable development.

Keywords: coal fly ash; coal bottom ash; brick; sand; cement; compressive strength; masonry prism

1. Introduction

Bricks play an inexorable role in construction industry. The production of bricks includes clay and shale; continuous removal of clay from soil makes it infertile because of depletion of valuable resources. Moreover, coal combustion residue is a big problem for power plants. Past studies show that bricks made from waste materials, such as fly ash, construction and demolition (C&D) waste, limestone powder, cement kiln dust are considerably good in its mechanical and physical properties (Zhang 2013). The construction industry of India alone produces 22% of greenhouse gases, carbon dioxide produced from cement industry is around 2070 million tonnes/year globally, whereas 148 million tonnes alone is produced from cement industry of India (Reddy 2009). India stands second in the production of bricks with 140 billion/year production and China stands first with production of 700-800 billion bricks/year (Baum 2010, Verma *et al*. 2016). These brick kilns releases harmful air pollutants, average emission of carbon monoxide observed was 6.35 kg to

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12.3 kg; SO_2 as 0.52 to 5.9 kg and particulate matter (PM) as 0.64 to 1.40 kg per 1000 bricks. The brick kilns of Kashmir valley have high concentration of SOx, NOx and PM which causes bad effects on environment, health as well as vegetation (Skinder *et al*. 2014). The United Nation development program showed that land eroded in India is about 83-163 million hectares annually which causes 4 to 6.3% productivity loss of total agricultural output (Kumar *et al*. 2014). The estimated growth of Bangladesh construction industry was around 5.6% annually that results in the significant increase in number of brick kilns. The carbon dioxide emission from these brick kilns was studied 15.67 million tons yearly. It was observed that 92% of the brickfields were highly polluting Fixed Chimney Kilns (Imran *et al*. 2014). The soil fertility analysed through physiochemical parameters of soil in Bhaktapur, Nepal where brick kilns are situated nearby, carbon content and organic matter varied from 0.28 to 0.93%, sulfate concentration in soil ranged from 0.829 to 3.764 mol/L and nitrate concentration in the soil ranged 0.98 to 29.99 mol/L, pH value varied from 5.89 to 7.64, water absorptivity of soil varied from 2.4 to 3.3mg/L (Bisht and Neupane 2015). Moreover, natural aggregates are depriving due to over exploitation of resources (Ashish and Saini 2018). Past investigations show that due to continuous erosion of soil, clay deposits are depleting at a faster rates globally and to overcome the problem, use of clay is minimized by some countries such as China has minimized use of clay in production of bricks (Abbas *et al*. 2017). The depletion of natural resources and environmental problems will govern sustainable development of construction materials (Ashish 2018).

There is a significant increase in amount of ashes in recent years and management of these ashes is a challenge for whole world. The number of researchers are working for the possible use of ashes globally. The ashes could be used in different areas such as agriculture, paint, ceramic, environment and construction depending upon their properties but most of the ashes produced are dumped in ash dumps and such similar places (Eliche-Quesada *et al*. 2017). The utilization of coal ash could lower environmental impact by providing alternative solutions to disposal problems and reducing CO_2 emissions (Opiso *et al*. 2017). The industrial waste generation in Malaysia was 1,705,308 metric tons in 2009, out of which 126,288 metric tons of industrial wastes were treated by Kualiti Alam Sdn Bhd, Malaysia and 25,000 tons of bottom ash was produced on disposal of these wastes (Naganathan *et al*. 2012). The consumption of fly ash in construction industry is 47% of the total fly ash produced whereas use of bottom ash limits to only 5.28% (Antoni *et al*. 2017). Use of bottom ash is generally restrained due to distinct, rough and angular shape particles that provides interlocking between particles (Kim 2015, Singh and Siddique 2015). The bottom ash is generally dumped in ash ponds which incur high costs. Moreover, excessive amount of bottom ash can result in possibility of leachate. Bottom ash could be replaced with fine aggregate in concrete due to its bigger size compared to fly ash. Size of bottom ash varies from 0.06 mm to 20 mm whereas 90% particle size of bottom ash is generally less than 6 mm (Marto and Tan 2016).The fused and glassy texture of coal ash makes it optimum for substitution (Kurama and Kaya 2008). Fly ash can be used at various purposes but due to high carbon content there is limited usage of coal bottom ash (Manz 1997). The brick prepared using fly ash, bottom ash and cement at an optimum ratio showed stronger and durable brick compared to conventional bricks (Naganathan *et al*. (2015). The paper investigates performance of bricks made using coal ash. Previous studies show bulk consumption of fly ash but bottom ash is generally avoided due to its discrete physical properties. This study explores the use of bottom ash to its maximum with minimum amount of cement to contribute towards sustainability.

2. Research significance

The researchers around the world are involved in use of waste materials as an alternative to natural resources for brick manufacturing. Due to continuous erosion of land, natural resources are depleting at faster rates so it becomes necessary to find new alternative construction materials for sustainable development. Moreover, inefficient management of waste material is one of the biggest problems rising globally. The present situation demands for new methodologies for effective use of waste materials that lead to decreased use of natural resources.

The present research investigates the usage of coal bottom ash for the manufacturing of bricks. Usage of coal fly ash and coal bottom ash can solve the problem of disposal of ashes and give way to sustainable development. This study explores the effect of coal bottom ash on durability and strength properties of coal ash bricks.

3. Experimental method

3.1 Materials used

Ordinary Portland cement (OPC) of 43 Grade from a single batch was used for all coal ash bricks. Cement taken was fresh and without any lumps. The cement was conforming to IS: 8112

Table 1 Chemical properties of coal ash and cement

Chemical component	Materials		
	Coal fly ash	Coal bottom ash	Cement
SiO_2	56.32	47.53	21.94
Al_2O_3	30.87	20.69	5.85
Fe_2O_3	4.94	0.76	2.50
K_2O	-	2.55	0.37
CaO	1.58	4.17	65.30
TiO_2	-	1.30	-
SO_3	-	1.00	1.60
Na_2O	-	0.33	0.95
MgO	0.70	0.82	0.90

Table 2 Physical properties of coal ash and cement

Properties	Coal fly ash	Coal bottom ash	Cement
Bulk density in kg/m^3	1000	-	-
Surface area in m^2/kg	468	-	
Specific gravity	2.03	1.39	3.14
Lime reactivity in N/mm^2	5.98	-	-
Water Absorption by mass (%)	-	31.58	-
Fineness modulus	-	1.45	
Loss of ignition	4.52	1.00	2.00

Table 3 Proportions of coal ash brick mixtures

Sr. No.	Mixture	Fly ash	Bottom ash	Sand	Cement
1	M-1	1	0.00	1	0.05
2	M-2	1	0.00	1	0.10
3	M-3	1	0.00	1	0.15
4	M-4	1	0.25	0.75	0.05
5	M-5	1	0.25	0.75	0.10
6	M-6	1	0.25	0.75	0.15
7	M-7	1	0.50	0.50	0.05
8	M-8	1	0.50	0.50	0.10
9	M-9	1	0.50	0.50	0.15
10	M-10	1	0.75	0.25	0.05
11	M-11	1	0.75	0.25	0.10
12	M-12	1	0.75	0.25	0.15
13	M-13	1	1	0.00	0.05
14	M-14	1	1	0.00	0.10
15	M-15	1	1	0.00	0.15

(1989). Coal ash was procured from Guru Nanak Dev Thermal Power plant (GNDTP), Bathinda, India. The procedure in IS: 2386-3 (1963) was used to measure water absorption of coal bottom ash. The main components of the coal bottom ash includes SiO_2 and Al_2O_3 that counts for more than 65% of total, detailed composition is given in Table 1. Physical properties of coal fly ash and coal bottom ash are given in Table 2. Locally procured natural sand was used. Sand was first sieved through 4.75 mm sieve to remove any particles greater than 4.75 mm and washed to remove the lumps of clay and other foreign material. It conformed to grading Zone-II form IS: 383 (1970) with specific gravity 2.63 and water absorption 2.76%. The fineness modulus of coal bottom ash and natural sand was 1.45 and 2.60, respectively.

3.2 Manufacturing of coal ash bricks

Table 3 depicts the mix proportions of coal ash bricks. For the manufacturing process of coal ash bricks 15 samples were produced. In the procedure cement, sand and bottom ash were mixed in dry form in mixer for 2 minutes after which fly ash was added and dry mixed for other 2 minutes. Due to light weight of fly ash, mixer was covered tightly to avoid volatility. After 2 minutes of dry material mixing water was added and again mixed for 2 minutes. With reference to the procedure specified in ASTM D 6103 (2000), flowability test was applied to mixture. The sample is considered flowable once spread diameter is at least 200 mm according to ACI 229R (1999). The essential flowability was achieved by adjusting water content. The brick moulds of size (230 mm×110 mm×75 mm) were filled with mixture and top surface levelled. The top surface of moulds were covered with wet cloth and kept in laboratory for 2 days. The specimens were removed and cured for 28 days.

3.3 Test procedure

The brick samples were tested in accordance with ASTM C 67 (2003) bricks were tested for density, compressive strength, modulus of rupture, water absorption and efflorescence.

For density and compressive strength the brick samples were oven dried for 24 hours at 110℃, cooled at room temperature and then weighed. The density of material was obtained by dividing the results over the average area. Universal testing machine was used having capacity 1000 kN for testing the brick specimens at 28 days of curing. For testing modulus of rupture, length of span was 175 mm and universal testing machine was used.

For durability properties, brick specimens were tested for water absorption and efflorescence. The specimens were dried and submerged at room temperature for 24 hours in clean water. After scheduled time, brick specimens were removed from water and wiped off to clean excess of water. The brick specimens were immersed in water for one minute up to 5 mm depth after drying. The specimens were removed and weighed.

In accordance to BS 1881-203 (1986) UPV test was conducted at 28 days. The test was conducted to access the quality and uniformity of material. It is a function of elastic modulus and strength of materials.

In accordance to IS: 1905 (1987), compressive strength was conducted of masonry prior to construction by tests, similar prisms were built for the structure under same bonding arrangement. In testing machine, prisms were tested between nominal 4 mm plywood sheets after 28 days of curing. The load applied to the specimen at the rate 350 to 700 kN/m was distributed evenly over top and bottom surfaces.

4. Result and discussion

4.1 Mechanical properties of coal ash brick

4.1.1 Density

The density of brick specimens are depicted in Fig. 1. When fly ash to cement ratio 1:0.05, decrease in density was observed in brick specimens having bottom ash in replacement of sand relative to brick specimens without bottom ash. With replacement of 25% sand by bottom ash, decrease in density observed was 2.5%. As replacement percentage of bottom ash increases, density of brick specimens decreases. Figure shows at replacement levels 50%, 75% and 100% decrease in density was 7.7%, 10.4% and 28.1%, respectively. When fly ash to cement ratio 1:0.10, specimens having bottom ash showed decrease in density as compared to specimens without bottom ash. With the increase in replacement percentage of bottom ash, density of brick specimens decreases. Figure shows at replacement levels 25%, 50%, 75% and 100% decrease in density was 3.5%, 7.9%, 10.4% and 26.6%, respectively. When fly ash to cement ratio 1:0.15, specimens having bottom ash showed decrease in density as compared to specimens without bottom ash. With the increase in replacement percentage of bottom ash, density of brick specimens decreases. Figure shows at replacement levels 25%, 50%, 75% and 100% decrease in density was 5.1%, 7.7%, 11.2% and 26.3%, respectively. Bottom ash bricks showed lower density in comparison to bricks without bottom ash due to lower specific gravity of bottom ash.

The density of brick specimens having bottom ash in replacement of 0%, 25%, 50%, 75% and 100% sand showed a noticeable increase with the increase in cement content. For 0% replacement,

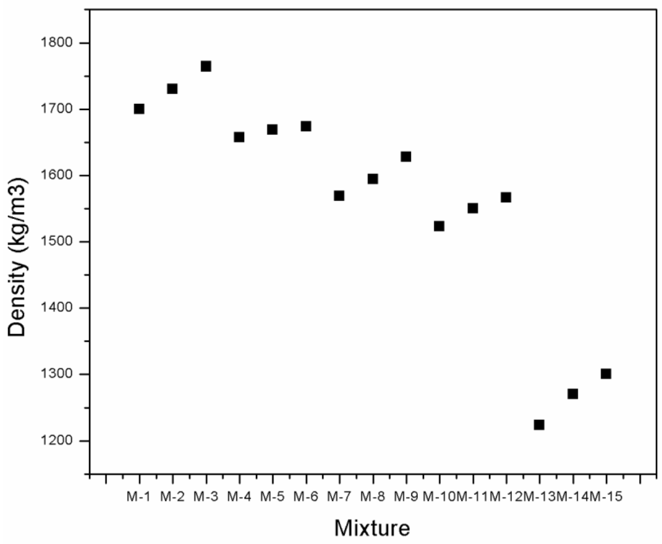


Fig. 1 Effect of coal bottom ash on density of coal ash bricks

fly ash to cement ratio 1:0.10 and 1:0.15, increase in density observed was 1.8% and 3.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 25% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in density observed was 0.7% and 1.0%, respectively, relative to fly ash-cement ratio 1:0.05. For 50% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in density observed was 1.6% and 3.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 75% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in density observed was 1.8% and 2.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 100% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in density observed was 3.8% and 6.3%, respectively, relative to fly ash-cement ratio 1:0.05. In coal ash brick production, the density mainly depends upon the specific gravity of constituent materials (Kunchariyakun *et al*. 2015, Li *et al*. 2018). This is due to higher specific gravity of cement relative to fly ash as well as sand and bottom ash. The higher density could also be due to higher cement content that resulted in decreased pore size.

4.1.2 Compressive strength

As depicted in Fig. 2, compressive strength ranged from 1.16 MPa to 9.39 MPa. The results shows that brick specimens manufactured using bottom ash and cement have highest compressive strength. For the bricks manufactured using bottom ash and cement, the highest compressive strength of mixes M-9, M-12 and M-15 was 8.23 MPa, 8.58 MPa and 9.39 MPa, respectively. The optimal results with maximum strength shows bottom ash, fly ash, sand and cement proportion as 1:1:0:0.15 with highest bottom ash content. The compressive strength is mainly governed by amount of hydration produced, but an important role is played by porosity and pore structure. Bottom ash present in coal ash bricks plays role of aerating agent, moreover, it is a silicious source in the production of bricks (Li *et al*. 2018). Due to presence of siliceous material hydration is accelerated.

When fly ash to cement ratio 1:0.05, the brick specimens having bottom ash in replacement of sand showed increase in compressive strength relative to brick specimens without bottom ash. On replacement of 25% sand with bottom ash, increase in compressive strength observed was 5.2%.

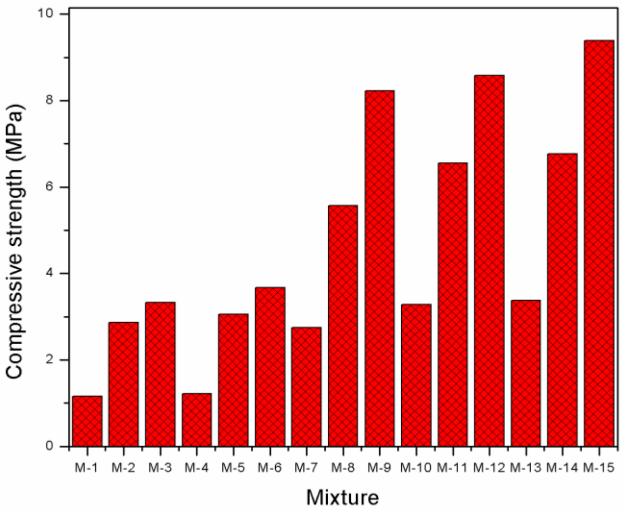


Fig. 2 Effect of coal bottom ash on compressive strength of coal ash bricks

With the increase in replacement percentage of bottom ash, compressive strength of brick specimens increases. It is clear from the figure that at replacement levels 50%, 75% and 100% increase in compressive strength was 137.1% and 182.8% and 191.4%, respectively. For fly ash to cement ratio 1:0.10, the brick specimens having bottom ash in replacement of sand showed increase in compressive strength relative to brick specimens without bottom ash. With the increase in replacement percentage of bottom ash, compressive strength of brick specimens increases. It is clear from figure that at replacement levels 25%, 50%, 75% and 100% increase in compressive strength was 6.3%, 94.1%, 128.6% and 135.9%, respectively. For fly ash to cement ratio 1:0.15, the brick specimens having bottom ash in replacement of sand showed increase in compressive strength relative to brick specimens without bottom ash. With the increase in replacement percentage of bottom ash, compressive strength of brick specimens increases. Figure shows at replacement levels 25%, 50%, 75% and 100% increase in compressive strength was 10.2%, 147.1%, 157.7% and 182.0%, respectively. Concrete containing above 25% bottom ash achieved required results of compressive strength, it could be due to joint effort of particle packing and pozzolanic activity of bottom ash.

The compressive strength of brick specimens having bottom ash in replacement of 0%, 25%, 50%, 75% and 100% sand showed a significant increase with the increase in cement content. For 0% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in compressive strength observed was 147.4% and 187.1%, respectively, relative to fly ash-cement ratio 1:0.05. For 25% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in compressive strength observed was 150.0% and 200.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 50% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in compressive strength observed was 102.3% and 199.3%, respectively, relative to fly ash-cement ratio 1:0.05. For 75% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in compressive strength observed was 100.0% and 161.6%, respectively, relative to fly ash-cement ratio 1:0.05. For 100% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in compressive strength observed was 100.3% and 177.8%, respectively, relative to fly ash-cement ratio 1:0.05. Increase in cement content could be responsible for the increase in strength as presence of calcium oxide (CaO) accelerate the hydration process. The persistent hydration in cement and pozzolanic reaction of the coal ash could be responsible for the strength gain in bottom ash bricks.

4.1.3 Modulus of rupture

Modulus of rupture of all brick specimens is depicted in Fig. 3. It varies from 1.70 to 12.78. It is clear from the figure that brick specimens using bottom ash and cement have highest modulus of rupture. For brick specimens using bottom ash and cement, the highest modulus of rupture for mixes M-9, M-12 and M-15 was 12.26 MPa, 12.61 MPa and 12.78 MPa, respectively. The increase in bottom ash and cement content increased strength of coal ash brick. The investigations shows optimal results for modulus of rupture for mixes prepared with bottom ash, fly ash, sand and cement proportion as 1:1:0:0.15.

For fly ash to cement ratio 1:0.05, increase in modulus of rupture was observed for the brick specimens having bottom ash in replacement of sand relative to brick specimens without bottom ash. When 25% sand was replaced by bottom ash, increase in modulus of rupture observed was 14.7%. With the increase in replacement percentage of bottom ash, modulus of rupture of brick specimens increases. It is clear from the figure that at replacement levels 50%, 75% and 100% increase in modulus of rupture was 122.9% and 226.5% and 255.9%, respectively. For fly ash to cement ratio 1:0.10, the brick specimens having bottom ash in replacement of sand showed increase in modulus of rupture relative to brick specimens without bottom ash. With the increase in replacement percentage of bottom ash, modulus of rupture of brick specimens increases. It is clear from figure that at replacement levels 25%, 50%, 75% and 100% increase in modulus of rupture was 11.2%, 72.5%, 64.9% and 73.6%, respectively. For fly ash to cement ratio 1:0.15, the brick specimens having bottom ash in replacement of sand showed increase in modulus of rupture relative to brick specimens without bottom ash. With the increase in replacement percentage of bottom ash, modulus of rupture of brick specimens increases. Figure shows at replacement levels 25%, 50%, 75% and 100% increase in modulus of rupture was 10.6%, 144.2%, 151.2% and 154.0%, respectively. Concrete containing above 25% bottom ash achieved required results of modulus of rupture, it could be due to enhanced results of compressive strength that lead to enhanced modulus of rupture as the factors that improved compressive strength would also improve modulus of rupture.

The modulus of rupture of brick specimens having bottom ash in replacement of 0%, 25%, 50%, 75% and 100% sand showed a significant increase with the increase in cement content. For 0% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in modulus of rupture observed was 156.5% and 195.3%, respectively, relative to fly ash-cement ratio 1:0.05. For 25% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in modulus of rupture observed was 148.7% and 184.6%, respectively, relative to fly ash-cement ratio 1:0.05. For 50% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in modulus of rupture observed was 52.0% and 177.0%, respectively, relative to fly ash-cement ratio 1:0.05. For 75% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in modulus of rupture observed was 61.3% and 158.9%, respectively, relative to fly ash-cement ratio 1:0.05. For 100% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in modulus of rupture observed was 25.1% and 111.2%, respectively, relative to fly ash-cement ratio 1:0.05. The improved results are observed with same amount of bottom ash and fly ash. The equal amounts of bottom ash and fly ash shows finest results may be due to filling of matrix by gel pore and makes mix solid (Manz 1997). The presence of bottom ash and cement in coal ash brick showed increase in modulus of rupture due to reaction of siliceous material available in bottom ash with calcium oxide in presence of water. With the

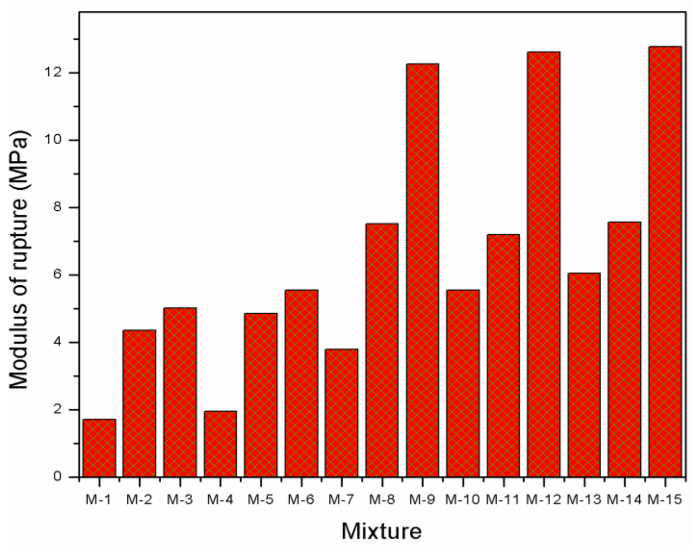


Fig. 3 Effect of coal bottom ash on modulus of rupture of coal ash bricks

increase in replacement of sand with bottom ash, compressive strength tends to increase resulting in higher modulus of rupture of coal ash brick. Modulus of rupture is greatly affected by porosity and pore structure of coal ash bricks, so, increase in compressive strength with decrease in porosity can lead to rise in modulus of rupture.

4.1.4 Ultrasonic pulse velocity

The UPV values varies from 0.75 km/s to 2.48 km/s presented in Fig. 4. It shows high UPV values for specimens using bottom ash and cement. In figure, it can be noticed that increase in bottom ash and cement content increases value of UPV in mixes. The UPV values for cement bricks was observed 1.50 km/s and UPV values for clay bricks was observed 0.79 km/s (Naganathan and Razak 2010). The investigations show optimal results of UPV for mixes prepared with bottom ash, fly ash, sand and cement proportions as 1:0.75:0.25:0.15. For brick specimens using bottom ash and cement UPV values for M-9, M-12, M-15 was 2.43 km/s, 2.48 km/s and 2.45 km/s, respectively.

For fly ash to cement ratio 1:0.05, pulse velocity increased for the brick specimens on replacement of sand with bottom ash relative to brick specimens without bottom ash. An increase of 6.7% was observed on replacement of 25% sand with bottom ash. Pulse velocity of brick specimens increases with the increase in replacement percentage of bottom ash. It is clear from the figure that at replacement levels 50%, 75% and 100%, increase in pulse velocity was 52.0%, 133.3% and 168.0%, respectively. For fly ash to cement ratio 1:0.10, the brick specimens having bottom ash in replacement of sand showed increase in pulse velocity relative to brick specimens without bottom ash. Pulse velocity of brick specimens increased with the increase in replacement percentage of bottom ash. It is clear from figure that at replacement levels 25%, 50%, 75% and 100% increase in pulse velocity was 2.0%, 100.0%, 110.8% and 113.7%, respectively. For fly ash to cement ratio 1:0.15, the brick specimens having bottom ash in replacement of sand showed increase in pulse velocity relative to brick specimens without bottom ash. With the increase in replacement percentage of bottom ash, pulse velocity of brick specimens increases. Figure shows

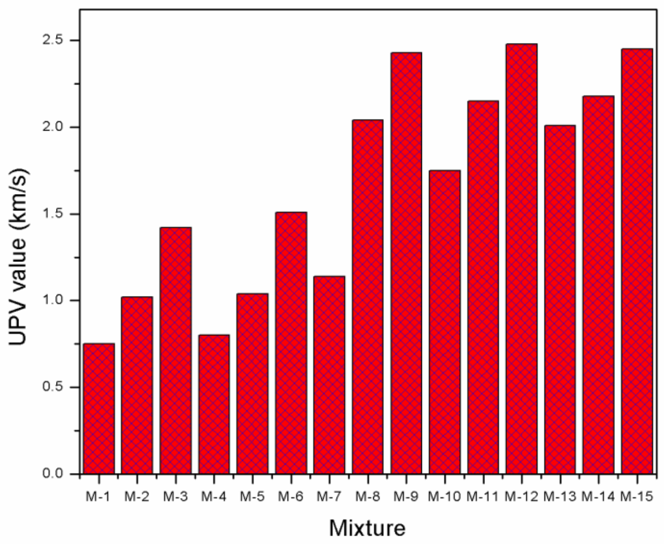


Fig. 4 Effect of coal bottom ash on UPV of coal ash bricks

at replacement levels 25%, 50%, 75% and 100% increase in pulse velocity was 6.3%, 71.1%, 74.6% and 72.5%, respectively. The increase in pulse velocity indicate the increase in the filler-void ratio as bottom ash is finer particle compared to sand. Moreover, enhanced results of pulse velocity shows the optimal quality of brick specimens in terms of density, homogeneity, and uniformity.

The pulse velocity of brick specimens having bottom ash in replacement of 0%, 25%, 50%, 75% and 100% sand showed a significant increase with the increase in cement content. For 0% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in pulse velocity observed was 36.0% and 89.3%, respectively, relative to fly ash-cement ratio 1:0.05. For 25% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in pulse velocity observed was 30.0% and 88.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 50% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in pulse velocity observed was 78.9% and 113.2%, respectively, relative to fly ash-cement ratio 1:0.05. For 75% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in pulse velocity observed was 22.9% and 41.7%, respectively, relative to fly ash-cement ratio 1:0.05. For 100% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, increase in pulse velocity observed was 8.5% and 21.9%, respectively, relative to fly ash-cement ratio 1:0.05. It could be due to increase in pulse velocity that indicate the increase in the calcium-silicate-hydrate and/or calcium aluminate hydrate gel-void ratio (Singh and Siddique 2015). The pulse velocity of brick samples are greatly affected with high cement content and related increase of density. Moreover, porosity and pore structure had a significant affect on coal ash brick. The increase in density, relatively decreases porosity resulting in significant rise in pulse velocity.

4.2 Durability properties of brick specimens

4.2.1 Water absorption

Water absorption of all brick specimens is shown in Fig. 5. It ranges from 12.39% to 18.39%. The mixes using bottom ash and cement have lower water absorption that can be seen in figure.

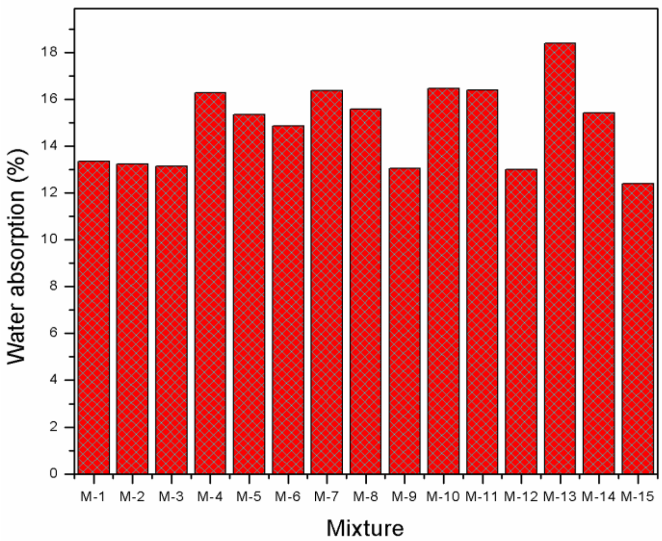


Fig. 5 Effect of coal bottom ash on water absorption of coal ash bricks

For brick specimens using bottom ash and cement, water absorption for M-9, M-12, M-15 was 13.05%, 13.00% and 12.39%, respectively. It was investigated that most of the bricks have high water absorption but these types of bricks can be used where weather exposure is minimum. The investigations shows optimal results of water absorption for mixes prepared with bottom ash, fly ash, sand and cement proportions as 1:1:0:0.15.

For fly ash to cement ratio 1:0.05, water absorption increased for the brick specimens on replacement of sand with bottom ash relative to brick specimens without bottom ash. An increase of 21.9% was observed on replacement of 25% sand with bottom ash. Water absorption of brick specimens increases with the increase in replacement percentage of bottom ash. It is clear from the figure that at replacement levels 50%, 75% and 100%, increase in water absorption was 22.5%, 23.2% and 37.6%, respectively. For fly ash to cement ratio 1:0.10, the brick specimens having bottom ash in replacement of sand showed increase in water absorption relative to brick specimens without bottom ash. Water absorption of brick specimens increased with the increase in replacement percentage of bottom ash. It is clear from figure that at replacement levels 25%, 50%, 75% and 100% increase in water absorption was 10.0%, 11.8%, 17.5% and 10.6%, respectively. For fly ash to cement ratio 1:0.15, the brick specimens having bottom ash in replacement of sand showed variations in water absorption relative to brick specimens without bottom ash. At replacement level 25%, increase in water absorption was 7.1%. But at replacement levels 50%, 75% and 100% decrease in water absorption was 5.8%, 6.2%, and 10.5%, respectively.

The water absorption of brick specimens having bottom ash in replacement of 0%, 25%, 50%, 75% and 100% sand showed a significant decrease with the increase in cement content. For 0% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, decrease in water absorption observed was 0.9% and 1.6%, respectively, relative to fly ash-cement ratio 1:0.05. For 25% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, decrease in water absorption observed was 5.8% and 8.8%, respectively, relative to fly ash-cement ratio 1:0.05. For 50% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, decrease in water absorption observed was 4.8% and 20.3%, respectively, relative to fly ash-cement ratio 1:0.05. For 75% replacement, fly ash to cement ratio 1:0.10 and

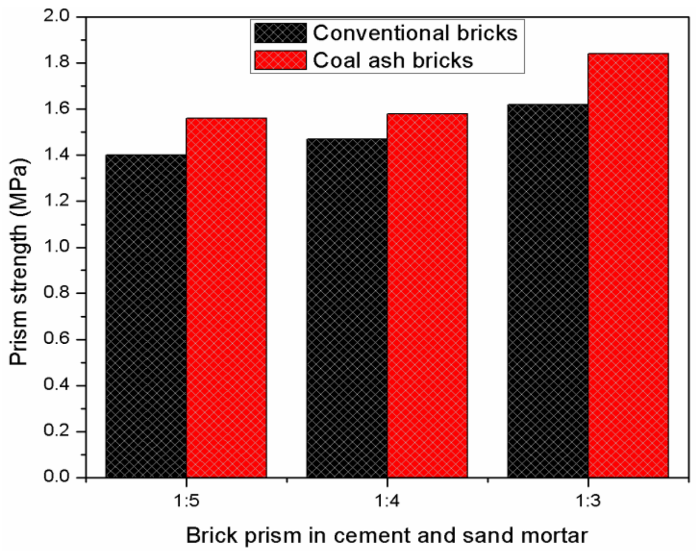


Fig. 6 Effect of coal bottom ash on masonry prism strength of coal ash bricks

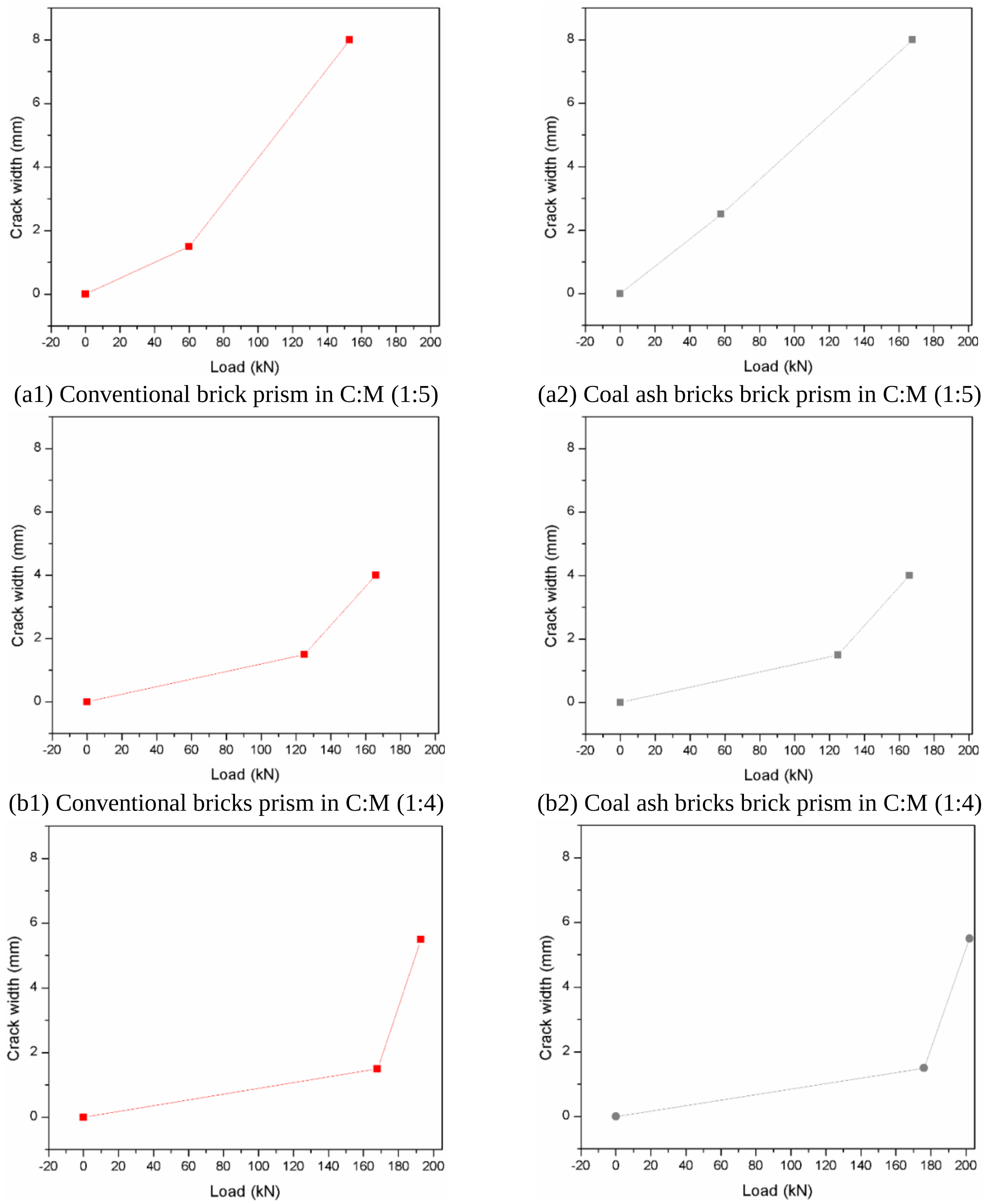
1:0.15, decrease in water absorption observed was 0.5% and 21.0%, respectively, relative to fly ash-cement ratio 1:0.05. For 100% replacement, fly ash to cement ratio 1:0.10 and 1:0.15, decrease in water absorption observed was 16.2% and 32.6%, respectively, relative to fly ash-cement ratio 1:0.05. The internal friction between the particles of coal bottom ash increased due to angular shape and rough texture of particles. Moreover, these particles are dry and porous and absorbed more water while mixing process of coal ash bricks that lead to lower amount of water in the inter particle voids for lubrication. Both the factors resulted in reduced water content and increased friction which lead to high water absorption of brick specimens with variable amount of bottom ash. The more the quantity of bottom ash, more is the absorption effect observed. Additionally, water absorption of brick samples are greatly affected with high cement content and related increase of pulse velocity. The water absorption is significantly affected with the porosity and pore structure of coal ash brick. The increase in pulse velocity, relatively decreases porosity resulting in significant drop in water absorption.

4.2.2 Efflorescence

The thin foggy white coloured salt deposit on brick surface that causes aesthetic problem is called efflorescence (Netinger *et al*. 2014). The coal ash brick specimens containing fly ash and bottom ash was observed with slight efflorescence whereas conventional specimens showed slight to moderate efflorescence (10% of surface area). The vital role is played by calcium oxide (CaO) in causing efflorescence (Netinger *et al.* 2014). The efflorescence behaviour is improved as the quantity of CaO reduces. Moreover, efflorescence can be caused by ferric oxide (Fe_2O_3) and less than 10% is recommended (Velasco *et al.* 2014).

4.2.5 Determination of compressive strength of masonry by prism test

Prism test results for 1:3, 1:4 and 1:5 cement mortars are shown in Fig. 6 for coal ash bricks and conventional bricks. According to figure, cement mortar (1:3) the average crushing strength of coal ash bricks was 1.84 MPa and for conventional bricks it was 1.62 MPa. Therefore, there was



(a1) Conventional brick prism in C:M (1:5)
(a2) Coal ash bricks brick prism in C:M (1:5)
(b1) Conventional bricks prism in C:M (1:4)
(b2) Coal ash bricks brick prism in C:M (1:4)
(c1) Conventional bricks prism in C:M (1:3)
(c2) Coal ash bricks prism in C:M (1:3)

Fig. 7 Relationships between crack width and load applied for bricks

11.96% increase in the crushing strength by prism test for coal ash bricks as compared to conventional bricks. With cement mortar (1:4) the average crushing strength of coal ash bricks was 1.58 MPa and for conventional bricks it was 1.47 MPa. Therefore, there was 6.97% increase in the crushing strength by prism test for coal ash bricks as compared to conventional bricks. With cement mortar (1:5) the average crushing strength of coal ash bricks was 1.40 MPa and for conventional bricks it was 1.56 MPa. Therefore, there was 10.25% increase in the crushing strength by prism test for coal ash bricks as compared to conventional bricks.

As shown in the Fig. 7(a1), during the testing of masonry prisms prepared using conventional brick in cement and sand mortar (C:M) 1:5, the maximum width of crack appeared to be 1.50 mm on the application of load 60 kN and on applying load 153 kN again the crack was measured to be maximum width of 8 mm. As shown in the Fig. 7(a2), during the testing of masonry prisms made using coal ash brick in C:M (1:5), the maximum width of crack appeared to be 2.5 mm on the application of load 58 kN and on applying load 168 kN again the crack width was measured with the maximum width of 8 mm.

As shown in the Fig. 7(b1), during the testing of masonry prisms made using conventional brick in C:M (1:4), the maximum width of crack appeared to be 1.50 mm on the application of load 125 kN and on applying load of 166 kN again the crack was measured with the maximum width of 4 mm. As shown in the Fig. 7(b2), during the testing of masonry prisms made using coal ash brick in C:M (1:4) the maximum width of crack appeared to be 1.50 mm on the application of load 152 kN and on applying load of 184 kN again the crack width was measured with the maximum width of 4 mm.

As shown in the Fig. 7(c1), during the testing of masonry prisms made using conventional brick in C:M (1:3) the maximum width of crack appeared to be 1.50 mm on the application of load 168 kN and on applying load of 193 kN again the crack was measured with the maximum width of 5.5 mm. As shown in the Fig. 7(c2), during the testing of masonry prisms made using coal ash brick in C:M (1:3) the maximum width of crack appeared to be 1.50 mm on the application load of 176 kN and on applying load of 202 kN again the crack was measured with the maximum width of 5.5 mm.

Test results showed coal ash bricks better compared to conventional bricks due to presence of bottom ash. Properties of fly ash bricks are good but results are not satisfactory in prism test as joints of brick and mortar weakens (Dar *et al*. 2015). This is due to micro fine particles of fly ash which makes surface of bricks smooth. Whereas, presence of bottom ash increases internal friction due to rough texture of particles which makes mortar and coal ash brick in masonary well bonded.

5. Conclusions

On the basis of results obtained in present study, the following conclusions can be drawn.

- The compressive strength and modulus of rupture of coal ash bricks increased with the increase in bottom ash. The highest compressive strength of coal ash brick achieved was 9.39 MPa and highest modulus of rupture was 12.78 MPa. The optimal compressive strength and modulus of rupture was achieved for the mix with bottom ash, fly ash and cement proportion as 1:1:0.15.
- UPV values of coal ash bricks increased with the increase in bottom ash. Highest UPV values of coal ash brick observed was 2.48 km/s. The optimal UPV values were achieved for the mix with bottom ash, fly ash and sand proportion as 1:0.75:0.25 and fly ash-cement ratio as 0.15.
- The investigations shows that coal ash bricks developed were durable compared to bricks made without bottom ash. It was observed that bricks developed were stronger with low rate of water absorption and efflorescence.

• In prism test, it was observed that performance of coal ash bricks with bottom ash shows optimal results as compared to conventional brick~~s~~.

The highest performance in coal ash bricks was observed with bottom ash, fly ash and cement ratio as 1:1:0.15, it can be concluded that bricks developed with coal ash could be viable solution to sustainable development.

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