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Comparative feasibility analysis of fly ash bricks, clay bricks and fly ash incorporated clay bricks

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Abstract. Recycling of industrial wastes like fly ash into construction materials is attaining more momentum nowadays towards enhancing the characteristics and performance of materials in terms of strength and durability. This article attempts to present the effect of fly ash inclusion on the properties of bricks through a comparative feasibility analysis of fly ash bricks (FB), clay bricks (CB), and fly ash incorporated clay bricks (FC). For experimentation, twelve brick specimens were made using fly ash, clay, lime, gypsum, sand, and water in different proportions followed by sun-drying and firing methods. Sieve analysis, X-ray diffraction (XRD), Scanning electron microscope (SEM), Energy Dispersive X-ray Fluorescence (EDXRF), Fourier-transform infrared spectroscopy (FTIR), compressive strength, and efflorescence tests were performed to study the properties of brick specimens. Various factors such as the effect of drying, heating temperature, and percentage of ash addition on the bricks were also observed. The laboratory results indicated that out of the above-mentioned three bricks, FB showed better performance than CB and FC. The compressive strength and water absorption values for FB were found in the range of 8.50–12.18 MPa and 10.84–13.11 %, respectively. Thus, based on the experimental observations and results, the mix design FB-3 (25 % fly ash, 20 % lime, 2 % gypsum, 53 % sand) exhibited the optimum compressive strength of 10.25 MPa with a water absorption value of 11.16 %. This mix design can be recommended as a substitute for conventional bricks against aggressive environment contributing immensely towards solid waste management and sustainable development.

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1. Introduction

The history of brick manufacturing is dating back to 8000 BC. Brick is considered one of the most important raw materials for construction purpose [1]. The use of fly ash during brick manufacturing is a significant step towards waste management, resource conservation, and sustainable development, as brick manufacturing requires a substantial amount of natural resources, mostly clay, leading to resource depletion as well as negative effects on the surrounding ecosystem [2]. On the other hand, fly ash is a waste material disposed of in and around the Thermal Power Plants (TPPs). Therefore, the use of coal fly ash (CFA) during brick making can be a feasible alternative and will reduce environmental burden [3]; but the use of CFA during brick manufacturing needs to be explored in every dimension so that its use can be environmentally friendly and sustainable. Approximately 30 % of the world population use clay bricks for constructing their accommodations and other buildings [4, 5]. Bricks are generally prepared by moulding clay mixture in block forms, followed by sun drying and firing. Burnt clay bricks can achieve better strength than sun-dried bricks. The different factors such as the nature of material and manufacturing process affect the properties of the bricks [6, 7]. Temperature is also another key parameter that controls the development of bricks [8–10]. It helps in melting of oxides and silica present in the clay. After cooling, a bond forms between the clay particles [5, 6]. Nearly 300 million tonnes of fertile soil is consumed per day in India for brick manufacturing [11–13]. Similarly, 700 million tonnes of clay bricks are manufactured every year in Ontario, Canada [8]. As a consequence, clay deposits are depleting fast in various parts of the world due to rapid urbanization, commercialization, and industrialization. To put a brake on the decreasing levels of soil deposits, countries like China and India restricted the use of clay in brick manufacturing [14, 15]. It has also been reported that these bricks are low in strength and durability. To overcome these shortcomings, some pozzolanic material may be added to bricks to increase the strength of the material [16–18]. In the past decade various waste materials have been incorporated in clay bricks to improve compressive strength and water absorption values [19–21].

The purpose of this paper is to throw some light on the effect of fabrication process, variation of constituent materials, ash content on different physicochemical and mechanical properties of three types of brick specimens. The key factors taken into consideration are fly ash to binder ratio, drying and heating temperatures, and incorporation of fly ash content in clay brick.

2. Methods

2.1. Raw materials

The materials used in making of brick specimens were Class-F fly ash (as per ASTM C618 standard), clay, lime, gypsum, and water. Fly ash and clay were procured from NALCO, Anugul and Brahmani river bed, and Odisha, respectively. Lime was used as a binding agent and gypsum was used as a long-term strength gainer in bricks. The 2 mm passing and 1 mm retained sand size was used in the brick mix design. The water to cement ratio of 0.45 was used uniformly in all the mixtures.

2.2. Fabrication of brick specimens

In this method, three varieties of bricks, viz. fly ash bricks (FB), clay bricks (CB), and fly ash incorporated clay bricks (FC), were prepared. Brick techniques such as hand mixing followed by sun drying and heating were adopted for brick manufacturing. The schematic representation of FB, CB and FC preparation is given in Fig. 1.

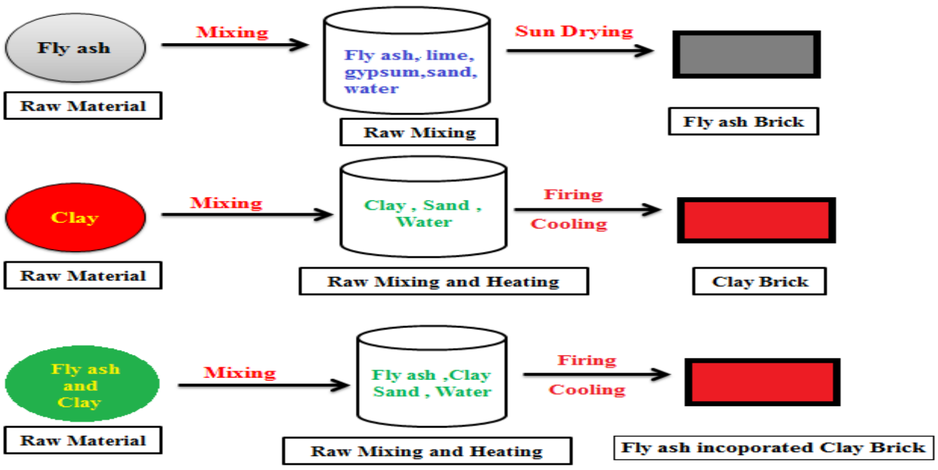


Figure 1. Schematic representation of preparation of brick specimens.

The methodology of FC making was quite similar to that of clay brick. In FC, fly ash was added to clay in different ratios. The ingredients required for the fabrication of bricks were fly ash, clay, lime, gypsum, and water. These materials were taken in different proportions and mixed in a disc and a calculated amount of water was added to get a homogeneous mixture. The mixed proportions of brick specimens are given in Table 1. An automated brick production unit was used to prepare the bricks of standard 190×90×90 mm^3 size as per Indian standard IS 12894 (Bureau of Indian Standards, 2011). A flat pan mixer and two rollers attached to the brick production unit effectively mixed and grinded the raw materials. Such type of arrangement is more beneficial for mixing of the raw material; however, it limits the mixing capability.

Table 1. Mix proportions of FB, CB, and FC.

			FB		
Mix ID	Fly ash (%)	Clay (%)	Lime (%)	Gypsum (%)	Sand (%)
FB-1	15	------	30	2	53
FB-2	20	------	25	2	53
FB-3	25	------	20	2	53
FB-4	30	------	15	2	53
FB-5	35	------	10	2	53
FB-6	40	------	5	2	53
			CB		
CB-7	------	100	------	------	------
			FC		
FC-8	5	95	------	------	------
FC-9	10	90	------	------	------
FC-10	15	85	------	------	------
FC-11	20	50	------	------	------
FC-12	25	75	------	------	------

2.3. Testing Methods

The physicochemical and mechanical properties of raw materials and bricks were examined as per Indian Standards by performing sieve analysis, XRD, SEM, FTIR, EDXRF, compressive strength (IS 3495, 2002), water absorption (IS 3495, 2002), and efflorescence tests (IS 3495, 2002). Some factors like sun drying, firing temperature, and constituent materials ratio which affect the properties of the brick production were also studied.

3. Results and Discussion

3.1. Characterization of Raw materials

3.1.1. Sieve analysis

The particle size distribution of fly ash and clay was analysed by using Malvern particle size analyser (Model Micro-P, range 0.05–550 micron). The particle size distribution of raw materials is shown in Fig. 2. Fly ash particles are much finer than the particles of clay. It is evident by the average particle size of 10 μm for fly ash and 86 μm for clay.

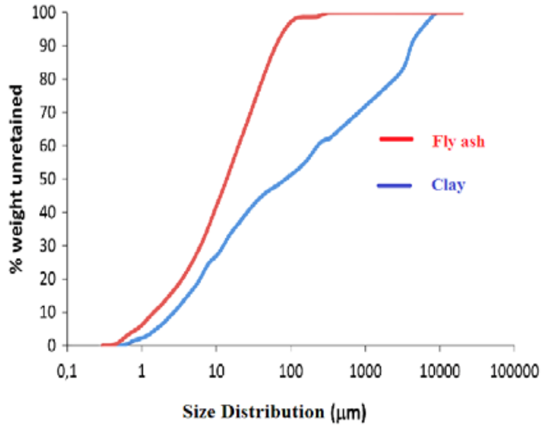


Figure 2. Particle size distribution of fly ash and clay.

3.1.2. Chemical analysis

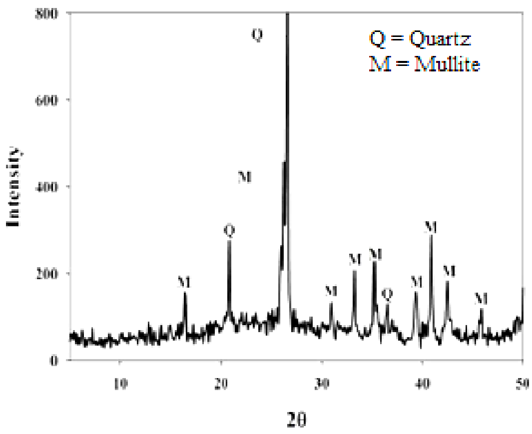
The chemical compositions of fly ash and clay were analysed by using EDXRF (Model no. EDX7000) and the results are tabulated in Table 2. Fly ash is mainly composed of silica, alumina, iron oxides calcium, manganese. The major Si content in fly ash is 59.512 %, while in clay it is 63.450 %. Similarly, Al and Fe contents are 26.078 % and 7.509 % in fly ash, whereas in clay they are 14.116 % and 13.409 %, respectively.

Table 2. EDXRF analysis of fly ash and clay.

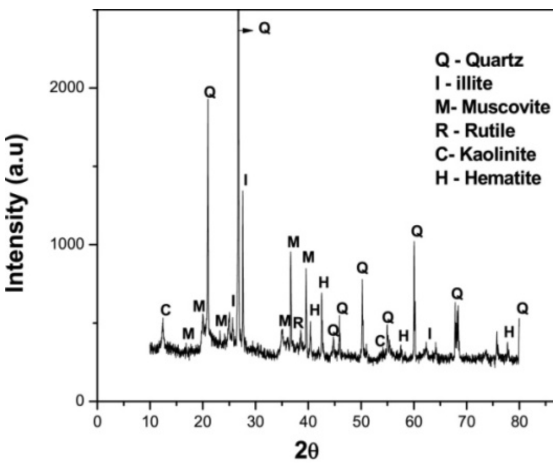
Fly ash									
Analyte	Si	Al	Fe	K	Ca	Mn	Cr	Pb	Zn
Result	59.512	26.078	7.509	1.888	1.492	0.075	0.048	0.024	0.039
Clay									
Analyte	Si	Al	Fe	K	Ca	Mn	Cr	Ir	Zn
Result	63.450	14.116	13.409	4.201	2.115	0.202	0.130	0.026	0.022

3.1.3. XRD and SEM analysis

The XRD pattern of fly ash and clay is shown in Fig. 3 (a, b). XRD pattern of coal fly ash shows small peaks which can be attributed to the presence of a small amount of quartz and mullite. But in clay, the major mineral phases are Quartz, Illite, Muscovite, Rutile, Kaolinite, and Hematite. The morphological study of fly ash shows that the samples mainly comprised small, spherical particles. SEM analysis of clay indicates the presence of particles of distinct angular sizes and to a lesser extent of spherical sizes. SEM micrographs of fly ash and clay are shown in Fig. 3 (c, d).

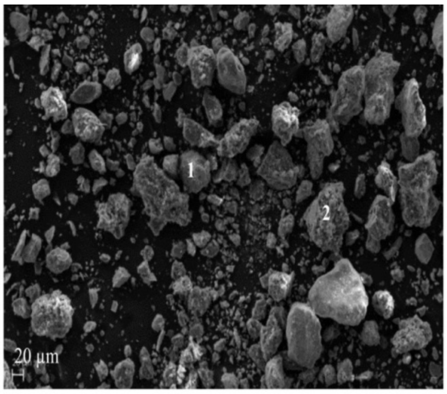


(a) XRD of fly ash



(b) XRD of clay

(c) SEM of fly ash



(d) SEM of clay

Figure 3. XRD and SEM analysis of fly ash and clay.

3.1.4. FTIR analysis of fly ash and clay

FTIR analysis of fly ash and clay is given in Fig. 4. The IR spectrum of fly ash shows bands at 3441, 3072, 3044, 2985, 2870, 2826, 1621, 1504, 1463, 1027, 694,541 cm^{-1}. In fly ash, broadband at 3441.21cm^{-1} is due to O–H stretching vibrations. The peak around 3100–3000 cm^{-1} may be due to some aromatic C–H stretching. Peaks at 2870.37 cm^{-1}, 2826.54 cm^{-1}, and 2985.76 cm^{-1} are due to the presence of organic carbon. A peak at 1621.09 cm^{-1} in the spectra indicates the adsorbed or associated water molecules (O–H bending frequency). The peaks at 1504.83 cm^{-1} and 1463.14 cm^{-1} may be assigned to carbonates present in the sample. The IR spectrum of clay shows bands at 3695, 3619, 3431, 3010, 2870, 2830, 1875, 1630, 1462, 1025, 778,694 cm^{-1}. The peak at 3695.83 cm^{-1} is due to the Si–O–H vibration of clays, kaolinite, and Fe oxides. The peak at 3431.02 cm^{-1} may be attributed to O–H stretching of H-bonded water. The peak at 3010.01 cm^{-1} is due to aromatic C–H stretching. The peaks at 2870.56 cm^{-1} and 2830.09 cm^{-1} are assigned to the presence of organic carbon. The peak at 1875.90 cm^{-1} is due to calcite (overtone/combination band). The peak observed at 1630.53 cm^{-1} corresponds to O–H bending vibration of water.

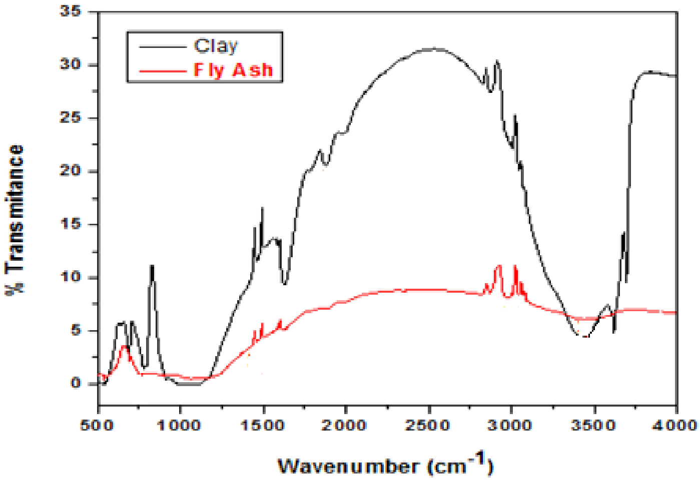


Figure 4. FTIR analysis of fly ash and clay.

3.2. Mechanical properties

3.2.1. Compressive strength and water absorption

The moisture content and mixing sequence plays an important role in the mechanical performance of bricks. Water absorption test on a brick is conducted to find out the amount of moisture content absorbed by the brick under excessive conditions. It also determines the durability of the brick specimens. Low water absorption represents high compressive strength, durability and good quality of brick. The strength of the bricks was tested using a compressive strength machine as shown in Fig. 5. Mechanical tests of the brick specimens were performed at KIIT Deemed to be University, Bhubaneswar. Around twelve brick specimens were used to study the effect on mechanical properties. Table 3 presents the compressive strength and water absorption values of different brick mixes. From the experimental results, it is clear that FB-1 showed the maximum compressive strength of 12.18 MPa with water absorption of 10.84 %. CB-7 received compressive strength of 7.88 MPa with a water absorption of 13.78 %. Similarly, FC-12 observed a low value of compressive strength (6.47 MPa) with a high value of water absorption (16.10 %). Overall, the mix design FB-3 showed the compressive strength of 10.25 MPa with water absorption of 11.16 %, which is the optimum and satisfied the basic requirement of the bricks. The optimal mix percentage of FB-3 was 25 % fly ash, 20 % lime, 2 % gypsum, and 53 % sand. As the compressive strength of the material increases, the water absorption value decreases. During the fabrication process of bricks, it was found that CB has some pores in its body structure in comparison to FB, which were responsible for a higher value of water absorption and lower value of compressive strength than those for FB. In case of FC, compressive strength decreased with the gradual increase in the percentage of fly ash. The compressive strength reduction increased by more than 50 %, with 20 % and 25 % fly ash add-ons. Therefore, it is concluded that FB showed better mechanical properties than CB and FC.

(a) Compressive strength of FB **(b) Compressive strength of CB**

Figure 5. Compressive strength analysis of FB and CB.

Table 3. Mechanical properties of different brick specimens.

Mix ID	Compressive strength (28 days)	Water absorption (%)
FB-1	12.18	10.84
FB-2	11.07	11.21
FB-3	10.25	11.66
FB-4	9.46	12.16
FB-5	9.10	12.74
FB-6	8.50	13.11
CB-7	7.88	13.78
FC-8	7.66	14.10
FC-9	7.48	14.58
FC-10	7.15	15.26
FC-11	6.78	15.85
FC-12	6.47	16.10

3.3. Effect of various parameters on brick specimens

3.3.1. Effect of constituent material and sun drying on FB strength properties

Fly ash, in presence of moisture, reacts with lime and gypsum to form compounds having cementitious properties. This property was used for FB production. Higher-strength bricks can be obtained by increasing lime content in the mixture. The lime reacts with oxide components like silica, alumina, and iron oxide of fly ash to develop different types of lime bearing phases like calcium silicate, calcium aluminate, calcium aluminosilicate, etc., and these phases are subsequently hydrated in the presence of water to form different hydrates. The moisture content of the brick decreased with an increase in the time of sun drying. The reason was that the moisture evaporation increased with the increase in time when the brick was dried in the environment under the sun. When the brick was dried, its moisture content was between 10–12 %, which is the atmospheric moisture content of the brick.

3.3.2. Effect of firing temperature on CB strength properties

Temperature is also another key parameter that controls the development of bricks. It helps to melt the oxides and silica present in the clay. After cooling, bond formation takes place within the clay particles. The fusibility of clay causes it to become hard and solid with a relatively low absorption when properly fired. This process improves the strength of the specimens. There is a relationship between the firing temperature and compressive strength. Compressive strength of bricks is remarkably improved by firing at higher temperatures. With increase in firing temperature (700–1000 °C), compressive strength was found to be increased.

3.3.3. Effect of ash content on FC strength properties

The compressive strength of FC decreased with a gradual increase in the percentage of fly ash. This is because, during the mixing process, when fly ash was incorporated, it didn't mix properly with clay, and simultaneously when it was allowed for heat treatment, the mass of the fly ash didn't fuse and remained as such in the bricks. It seems that the fly ash doesn’t react properly with clay to form bonding in FC.

3.4. Efflorescence test of FB, CB and FC

Generally, this test is carried out to know, if some soluble salts like magnesium sulfate, sodium sulfate, sodium carbonate, and potassium sulfate are present in the brick. A white deposition is seen in the brick specimen when immersed in water for 7 to 45 days. Then the bricks are allowed to dry for 60 days and observations are recorded for efflorescence. In case of CB and FC, a slight efflorescence of 8.5 % of the CB surface area was observed and its percentage decreased with the addition of fly ash in CB. But in FB, percentage of efflorescence was found to be negligible. The reason is that fly ash can bind salts and free lime, which causes a low percentage of efflorescence. Therefore, FB showed better performance in the efflorescence test. The efflorescence results on brick specimens are shown in Fig. 6.

(a) FB (b) CB (c) FC

Figure 6. Visual appearance of the different sets of bricks after the exposure period for efflorescence.

3.5. Effect of firing process on colour of CB

After the firing process there is a change in colour, mass and dimensions of bricks. The colour of bricks before the firing process was greyish-brown and grey. After firing process, due to the content of iron oxides, CB presented a red-orange colour, independent of the amount of incorporated residue, whereas in case of FB the colour was black and in FC the colour remained red.

3.6. Works by other authors

Pimraksa and Chindaprasirt [22] reported that the bricks made with untreated diatomite (with 15 % lime and 5 % gypsum) showed reasonably high strength of 14.5 MPa and low density of 0.88 g/cm^3 [22]. Miqueleiz et al. [23] studied the lightweight brick samples made with lime and coal ash (CA) waste, which tended to achieve higher strength values of 5 MPa. The compressive strength resistance reduced as the clay replacement level increased [23]. Muntohar and Rahman [24] developed lightweight masonry block made from oil palm kernelshell, which achieved the maximum strength of 22 MPa [24]. Eliche-Quesada et al. [25] manufactured CB using commercial clay and different waste ratios: fired at 1000 °C for 4 h, they showed the compressive strength value of 10 MPa [25]. Gourav and Venkatarama Reddy [26] reported that it is possible to produce fly ash-lime-gypsum bricks having 8–10 MPa wet compressive strength and reasonably low values of water absorption [26].

Table 4. Works by other authors.

Reference	Year	Observations
Pimraksa and Chindaprasirt [22]	2009	Brick showed compressive strength value of 14.5 MPa
Miqueleiz et al. [23]	2013	Brick made with fly ash showed compressive strength value of 5 MPa
Gourav and Venkatarama Reddy [26]	2014	Fly ash lime gypsum bricks showed compressive strength value of 8–10 MPa
Eliche-Quesada et al. [25]	2018	Fired CB showed compressive strength value of 10 MPa

4. Conclusions

In the present study, a comparative feasibility analysis was done for fly ash bricks (FB), clay bricks (CB), and fly ash incorporated clay bricks (FC). The following conclusions are drawn on the basis of experimental outcomes:

1. Fly ash rich in SiO_2 and Al_2O_3 has a chemical composition similar to that of clays used in the manufacturing of fired CB. Therefore, the use of fly ash may reduce the consumption of clay as a raw material for bricks.

2. A comparison in the bond strength in three types of bricks shows that FB has a better bond strength than standard CB and FC.

3. With the increase in firing temperature, the comprehensive strength of CB gradually increases. It is concluded that the compressive strength of the FC decreases with an increasing percentage of fly ash. Because when FC is exposed to firing at a certain temperature, the fly ash present in clay is not fused and doesn't mix with clay. It remains the same, so the bond between fly ash and clay does not form.

4. From the experimental results, mix design FB-1 showed the maximum compressive strength value of 12.18 MPa with the lowest water absorption of 10.84 %. Mix design FC-12 showed the lowest value of compressive strength 6.47 MPa with the highest value of water absorption, 16.10 %.

5. Mix design FB-3 (25 % fly ash, 20 % lime, 2 % gypsum, 53 % sand) exhibited the optimum compressive strength of 10.25 MPa with water absorption value of 11.16 % and is recommendable on the basis of experimental results.

6. FB showed better performance than CB and FC with respect to efflorescence. The efflorescence of 8.5 % was seen on the surface area of CB. It was observed that the efflorescence percentage decreases with the incorporation of fly ash in CB. For incorporation of 20 % and 25 % of fly ash in CB, the efflorescence percentage was found to be 3.8 % and 3.6 %, respectively.

7. Fly ash bricks are hi-tech bricks of improved quality used for construction and masonry structures. They are the best replacement for normal CB and have better mechanical properties. The fabrication of FB is cost-effective in terms of saving firing time, heating temperature, which are necessary steps in the case of CB. Overall, FB showed satisfactory performance as compared to CB and FC.

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