Reuse of fly ash and bottom ash in mortars with improved thermal conductivity performance for buildings

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Abstract

An approach towards effective utilization of fly ash and bottom ash in the construction of energy efficient buildings has been presented in this paper. Two masonry mortar grades MM3 and MM5 were considered for trial mix. Portland pozzolana cement with substitution of sand by fly ash and bottom ash separately in different substitution ratios (SR) were adopted for preparation of test samples. Fly ash and bottom ash with lime dust and marble dust combinations were also tested as sand free mortars. 28 days compressive strength, apparent porosity, bulk density and thermal conductivity parameters were evaluated for all such samples. By analysing the test results, it was observed that all the SR combinations satisfied the minimum masonry mortar grade MM0.7, as per IS 2250. Both the MM3 and MM5 grade mortars could be produced at 60% SR by fly ash, and corresponding reductions in thermal conductivity values were 69%, and 54% respectively, while compared with conventional mortar. Sand less mortar for both the grades resulted around 57% reductions in corresponding thermal conductivity values. Overall heat transfer co-efficient (U-value) for both side plastered and rendered brick masonry wall panel was found to be reduced by 15.58%, while comparison made between conventional mix of MM5 grade and corresponding 50% fly ash substituted mix. Thus such ash blended mortar
mix appears to be advantageous in building envelop application for lowering the overall cooling/heating demand of building, besides utilizing the coal ash up to largest extent and saving natural mineral sand from depletion.

Keywords: Civil engineering, Energy

1. Introduction

Considering the energy efficiency aspect of buildings to restrict the electrical energy demand, focus has been kept on the performance of building envelop. Building envelop performance directly influences operational energy and constituent materials directly impact embodied energy of the building. The design of the building envelop influences heat conduction through roof, opaque wall, and glazed windows and determine the quantum of sensible cooling/heating load. It also determines the amount of natural ventilation and day lighting. Due to rising frequency of hot and extreme weather events throughout the globe, the demand for space cooling is expected to triple between 2010 and 2050 (IEA, 2013). Thermal insulation and thermal mass have been used by building envelop designers for minimizing energy requirement. Since the commercially available insulations are manufactured from petroleum by-products, the cost and embodied energy content of those are very high. Choice of materials for energy efficient envelop construction should address issues of durability, ability of material to assist in passive design, local sourcing of materials to reduce transportation etc. For a conventional building, excluding fenestration area, balance opaque wall area is made up of brick-mortar-plaster combinations. The mortar and plaster compositions are normally made up of cement and sand of 1:6 (MM3 Grade) and 1:4 (MM5 Grade) proportions respectively.

Further, due to the growth in infrastructure sector, unprecedented sand mining from river bed is threatening the ecological balance seriously. On the other hand, 100% utilization of coal ash, which is generated from thermal power plants has not become possible till date. As a result of which, cumulative accumulation of the un-utilized ash each year in ash dykes are creating groundwater contamination, air pollution etc. The scenario of accumulated quantity of coal ash in India during last seven years period is shown under Table 1. In the present work, an effort has been made to replace sand by fly ash, bottom ash, fly ash- lime dust, bottom ash-lime dust, fly ash- marble dust and bottom ash- marble dust combinations in buildings’ wall mortar and plaster mix application, and to study the resultant effects from structural as well as thermal adequacy points of views. Further, overall heat transfer co-efficient or U-value of a conventional fired clay brick wall panel, both side plastered with PPC and 50% sand and 50% fly ash combination mix was measured and also compared with another identical panel with conventional mix with PPC and 100% sand. The utilization of fly ash and bottom ash in building mortar and plaster mix could
revolutionize the building construction industry. Earlier works by other researchers on fly ash and bottom ash usage for cement/sand replacement in concrete and mortar mixes in building construction are reviewed and discussed herein.

Aydin and Arel, 2017 investigated about the effects of high volume of fly ash in cement mix for low strength applications. Supplementary cementitious material in the mix was optimized and physical and mechanical properties were evaluated and predictive model was developed. The model could be followed for low strength application of cement paste. Gencel et al. (2015) had performed various physical and mechanical tests of mortars with fly ash as constituent fine aggregate material, and up to 70% ratio of fly ash-sand mortar was found acceptable without significant property change. Brake et al. (2017) had explored the re-usability of coal bottom ash as cement replacement in mortar. The bottom ash was made pulverized and the effect on workability and setting time were studied. Improvement in micro-structure of cement mortar could effectively increase the strength parameter of such product with lower Ca/Si ratio, as observed. Kim (2015) had experimented with sieved and ground coal bottom ash in high strength cement mortar. The bottom ash powder was observed to increase the workability and compressive strength values than the equivalent mortar made of cement and fly ash. Thaarrini and Ramasamy, 2015 proposed to utilize ground bottom ash in geo-polymer mortar. Influence of alkaline activator, Molar ratio and curing mode on compressive strength of such mortars were studied. With different molar ratio with different activator, improvement in compressive strength was observed under both ambient curing and steam curing atmospheres respectively. Demirboga (2003) had studied the effect of various mineral admixtures like fly ash, silica fume and blast furnace slag as cement replacement on thermal conductivity and compressive strength of mortar. In the experiment, it was observed that for 10, 20 and 30% replacement of cement by either of the admixtures, all mixes showed reduction in thermal conductivity but of varying degree. Silica fume showed highest reduction percentage, closely next was fly ash and blast furnace slag was

**Table 1.** Year wise Ash production from Thermal Power Plants in India.

| Year | Coal consumed (MMT) | Installed Capacity (GW) | Ash Produced (MMT) | Ash Utilized (MMT) | Ash Un-utilized (MMT) | Ash Utilized (%) | Avg. Ash content (%) |
|------|---------------------|-------------------------|--------------------|--------------------|-----------------------|-----------------|---------------------|
| 2016–17 | 509.46 | 157.377 | 169.25 | 107.10 | 62.15 | 63.28 | 33.22 |
| 2015–16 | 536.64 | 145.045 | 176.74 | 107.77 | 68.97 | 60.97 | 32.94 |
| 2014–15 | 549.72 | 138.916 | 184.14 | 102.54 | 81.60 | 55.69 | 33.50 |
| 2013–14 | 523.52 | 133.381 | 172.87 | 99.62 | 73.25 | 57.63 | 33.02 |
| 2012–13 | 482.97 | 120.312 | 163.56 | 100.37 | 63.19 | 61.37 | 33.87 |
| 2011–12 | 437.41 | 105.925 | 145.42 | 85.05 | 60.37 | 58.48 | 33.24 |
| 2010–11 | 407.61 | 80.458 | 131.09 | 73.13 | 57.96 | 55.79 | 32.16 |

Source: CEA Report (2010–11 to 2016–17).
distant third. All mixes exhibited decreasing compressive strength during early ages, and marginal increase in strength beyond 120 days of maturity. Herrera Duran A et al. (2016) had studied the thermal conductivity effect by introducing a novel co-polymer on ordinary Portland cement — Class F fly ash combination mortar with water reducing super-plasticizer. Mortars were made with three different water-binder ratios to arrive at an optimized ratio to reach a target 3.4 MPa compressive strength. The reduction in thermal conductivity to the tune of 33% exhibited identical result by commercially available cellular concrete. Shahidan et al. (2016) had studied the physical and chemical properties of coal bottom ash, as a replacement material for sand. Specific gravity, particle size distribution, density, Scanning electron microscopy and X-ray fluorescence test results indicated that the angular porous structure and the rough texture of bottom ash affected its particle density and specific gravity on the lower magnitude than that of sand. However the gradation of particles in bottom ash and sand showed some similarity, and overall, bottom ash is recommended favourably as a replacement material to sand. Abbas et al. (2016) had studied the effect of partial replacement of cement and sand by limestone dust and bottom ash respectively. Sand replacement by bottom ash was done from 10% to 40%, 60% and 80%, and cement replacement by limestone dust was fixed at 5% flat for all categories of mixes. At constant water-cement ratio, up to 30% replacement of sand and 5% replacement of cement, strength increased (compressive, flexural, split tensile), but above the replacement ratio, strength values found decreased. Sahmaran et al. (2006) assessed the self-compacting properties of mortars with four mineral additives like fly ash, brick powder, limestone powder and kaolinite. Besides, three superplasticizers and two viscosity modifiers were also used. Workability, setting time and hardened properties of mortars were evaluated. It was observed that fly ash and limestone powder mixing increased workability and setting time was increased by fly ash influence alone, which could be adjusted by the ternary mix of fly ash and limestone powder. Brick powder and kaolinite adversely affected workability criteria. When part of cement was replaced by mineral additives, reduction in strength was resulted. Rai et al. (2014) carried out experimental investigations on mortars, modified with quarry dust and fly ash in different ratios as substitute of sand and cement respectively. The compressive and transverse strength results revealed better order due to micro-filling and pozzolanic activities by the two substitutes. Ramadoss and Sundararajan, 2014 investigated about the suitability of lignite bottom ash as replacement of fine aggregate in masonry mortar. Among the various percentages tried, 20% replacement was found optimum from the point of view of mechanical strength adequacy including durability. Hardjito and Fing, 2010 studied the replacement effect of sand by bottom ash in geo-polymer mortar. It was found that the increase in bottom ash content reduced the compressive strength of geo-polymer mortar. Effect of temperature and addition of alkaline solution also affected the strength development negatively beyond certain points. Rafieizonooz et al. (2016, 2017) had tried to explore the effect of bottom ash and
fly ash in concrete, as replacement of sand and cement respectively. Sand was replaced at 20, 50, 75 and 100% rate and cement was replaced at flat 20% rate for all four proportions of sand replacement. Though there was no change in strength up to 28 days of curing, except reduced workability, but the strength found increased at 91 and 180 days maturity period. Due to such slow strength gain, such blended concrete was found appropriate in foundation, pavement construction etc. works. While exploring the toxicity and durability characteristics of such concrete in application, no adverse effect through leaching, sulphate and acid attack etc. were noticed. Such blended concrete with cement and sand replacement by fly ash and bottom ash was recommended as suitable replacement of clean construction materials. Brito et al. (2018) had reviewed all earlier works done by the other researchers on the environmental impact and toxicity characteristics of recycled concrete aggregates (rca), fly ash (fa), cement production as well as their substitution aspect. The analysis with respect to abiotic depletion potential, ozone depletion potential, photochemical ozone creation, acidification potential, eutrophication potential, toxicity, leachability etc. were considered. It was revealed that environmental impact and cost of concrete reduced considerably with such incorporations, and also requirement of landfill space reduced drastically. While incorporated in concrete, the leaching metals which were otherwise present in fly ash were also found diminished. Gourav et al. (2017) had studied different envelop materials about their structural and thermal properties. Table moulded conventional clay brick and fly ash-lime-gypsum (fal-G) brick were compared in the study, and fal-G brick was found to be a better option for masonry construction under tropical climatic condition. Vijayalakshmi et al. (2006) investigated the thermo-physical behaviour of opaque wall materials under the influence of solar radiation. Finite difference mathematical model was developed and the result was compared with actual test results of different combination wall elements on U-value, Temperature Time Delay and Decrement Factor parameters respectively. Bergey (2010) had presented the comparative study of various commercially available insulating materials, among which XPS was found to be having highest embodied global warming potential (GWP). Buddhi et al. (2012), had made comparison between fire-clay brick made construction and ash brick made construction for calculating energy and environment indices. Ash block was found to be better option for heat load reduction and saving of natural resources and environment.

2. Materials and methods

2.1. Materials used

For the purpose of this experiment, we had used commercially available Portland Pozzolana Cement (PPC) conforming IS 1489 Part 1 (1991, Reaffirmed 2005), conventional river sand conforming IS 383 (1970, Reaffirmed 2002), siliceous pulverized fuel ash (fly ash and bottom ash) obtained from thermal power plant, located
at Kolkata conforming IS 3812 Part 2 (2003), lime dust from local market and marble residue from the marble slab cutting and polishing industry, and potable quality water. No admixtures or additives or electro-mechanical mixer were used in this study.

2.1.1. Evaluation of various parameters of raw materials

The physical properties and chemical composition of the materials used in this study are shown in Tables 2 and 3 respectively. The specific gravity parameter of cement, sand, fly ash and bottom ash were determined as per IS 1528 (Pt. IX). The specific surface area of Portland pozzolana cement sample was mentioned in the test report, as supplied by the manufacturer, and that of flyash was tested by BET Analysis method with the help of Quantachrome Nova instrument. Quantitative chemical analysis of cement, flyash, bottomash, lime dust and marble dust were done by Wet Chemical method (for SiO$_2$, Al$_2$O$_3$, and LOI) and by ICPAES method (for balance parameters) respectively. The type of flyash and bottomash, both are of Class F variety as per ASTM C 618-12a (ASTM International, 2012), since the CaO < 10%, and the sum of silica, aluminium and iron oxide percentages is > 70%. The bottom ash particles have a very low LOI value. Since the bottom ash particles have a higher residence time in the furnace than the fly ash particles, the bottom ash particles are likely to lose more carbon and this results in a lower LOI value for bottom ash.

The grading curves in respect of sand and bottom ash were done as per IS 383 (1970, Reaffirmed 2002). The particle size analysis for flyash was carried out by Microtrac 3500S (micron range) LASER Diffraction System. The grading curves in respect of sand and bottom ash and particle size distribution curve in respect of fly ash are shown against Figs. 1, 2, and 3 respectively.

The samples of cement, sand, flyash and bottomash were prepared for XRD analysis using a back loading preparation method. Those were analyzed with a PANalyticalX’Pert’s Pro powder diffractometer with X’Celerator detector and variable divergence- and receiving slits with Fe filtered Cu-K$_\alpha$ radiation in a diffraction angle (2$\theta$) range of 15$^\circ$–89$^\circ$. The phases were identified using X’PertHighscore plus software. The relative phase amounts (weights %) were estimated using the Rietveld method (Autoquan Program). X-Ray Diffraction analysis, showing the constituent phases of

| Description of material          | Specific Gravity value | Sp. Surface area/Fineness Modulus          |
|--------------------------------|------------------------|--------------------------------------------|
| Portland Pozzolana Cement (PPC)| 3.043                  | Sp. Surface area: 444 m$^2$/kg.            |
| Fine Aggregate, Fly ash (FA)   | 2.434                  | Sp. Surface area: 552 m$^2$/kg.            |
| Fine Aggregate, Bottom ash (BA)| 2.246                  | Fineness Modulus: 1.446                    |
| Fine Aggregate, Sand           | 2.664                  | Fineness Modulus: 2.079                    |
Cement, flyash, bottomash and sand are shown against Figs. 4, 5, 6, and 7 respectively.

High Resolution Micro structural analysis by Field Emission Scanning Electron Microscopy (FESEM SUPRA 35VP) was carried out for fly ash, bottom ash and sand samples. Those are shown against Figs. 8, 9, and 10 respectively.

**Table 3. Chemical composition of Cement, FlyAsh, BottomAsh, Lime dust and Marble dust.**

| Chemical parameter (%) | Portland Pozzolana Cement (PPC) | Fly ash (FA) | Bottom ash (BA) | Lime dust | Marble dust |
|------------------------|---------------------------------|--------------|-----------------|-----------|-------------|
| SiO₂                   | 34.85                           | 61.86        | 60.71           | 12.92     | 14.28       |
| Al₂O₃                  | 10.65                           | 27.85        | 25.86           | 0.94      | 1.20        |
| TiO₂                   | 0.69                            | 2.20         | 6.81            | 0.12      | 0.78        |
| Fe₂O₃                  | 3.56                            | 2.63         | 1.97            | 0.11      | 0.82        |
| CaO                    | 43.96                           | 0.54         | 0.89            | 61.65     | 27.25       |
| MgO                    | 2.66                            | 0.47         | 0.63            | 0.97      | 17.76       |
| Na₂O                   | 0.30                            | 0.36         | 0.38            | 0.46      | 0.65        |
| K₂O                    | 1.10                            | 1.27         | 1.28            | 0.09      | 0.42        |
| L.O.I.                 | 1.89                            | 2.49         | 0.92            | 22.53     | 36.66       |

**Fig. 1.** Grading curve for Sand, used in the experiment (Fineness Modulus 2.079).
2.1.2. Preparation of samples

Two grades of masonry mortar MM3 and MM5 (corresponding 28 days compressive strength values should be no less than 3 N/mm² and 5 N/mm²) as per IS 2250 (1981, Reaffirmed 2000) were selected for evaluation. These two grades are conventionally used throughout the country, with Cement-sand ratios of 1:6 and 1:4 respectively. In the experimental work, sand was gradually replaced by fly ash in one series of mix (A-Series, A,-A-1,A-2,…., A-10), and by bottom ash in another (B-Series, B,B-1,B-2,….,B-10), within the same grade of mortar MM3 (Table 4). Similarly for another grade MM5, such combinations were followed (Table 5). Sand less mortars with fly ash, bottom ash and marble dust combinations under MM3 and MM5 Grade are shown against Tables 6 and 7 respectively. There were fifty different combinations of mortar mixes, among which two were control mix, wherein sand was used as fine aggregate conventionally. For each combination of mix, three nos. 50 mm* 50 mm*50 mm mortar cube moulds, and pairs of 50 mm*50 mm *12 mm mortar square moulds were prepared. The samples were de-moulded after 24 hours of casting and kept immersed in potable water till 28 days at room temperature. After 28 days of water curing, samples were taken out of water, wiped clean and kept at room temperature before performing subsequent tests. Three cubes were tested to determine

Fig. 2. Grading curve for Bottom ash, used in the experiment (Finess Modulus 1.446).
Fig. 3. Particle size distribution for fly ash, used in the experiment.

Fig. 4. XRD phase of PPC, used in the experiment.
Fig. 5. XRD phase of fly ash, used in the experiment.

Fig. 6. XRD phase of bottom ash, used in the experiment.
Fig. 7. XRD phase of sand, used in the experiment. Note: \( Q = \) Quartz, \( M = \) Mullite, \( A = \) Aluminium titanate, \( F = \) Fassaite \((\text{Ca}_{0.96}\text{Mg}_{0.57}\text{Fe}_{0.22}\text{Al}_{0.16}\text{Ti}_{0.059})\text{Si}_{1.73}\text{Al}_{0.27}\text{O}_6\), \( P = \) Pseudobrookite \((\text{Fe}_2\text{O}_3\cdot\text{TiO}_2)\), Hematite \((\text{Fe}_2\text{O}_3)\), Iron silicate \((\text{FeSiO}_3)\), Calcite \((\text{CaCO}_3)\), Hartrurite \((\text{Ca}_3\text{SiO}_4\text{O})\), Calcium aluminate oxide \((3\text{CaO}\cdot3\text{Al}_2\text{O}_3)\), Titanium iron oxide, Schorlomite \((\text{Ca}_3\text{Ti}_2(\text{Fe}_2\text{Si}_3)\text{O}_{12})\), Protoenstatite \((\text{MgSiO}_3)\), Hydromolysite \((\text{FeCl}_3\cdot6\text{H}_2\text{O})\).

Fig. 8. (a),(b),(c),(d) SEM images of Flyash under different magnifications.
compressive strength of each sample, and pairs of sample of 12 mm thickness were tested for thermal conductivity parameter respectively. After compiling all the test results, the C-5 mix was identified under MM5 mortar grade category, being the lowest complied mix with 50% substitution of sand by flyash with thermal conductivity value reduction to the tune of 49.31%, in comparison with control mix with 100% sand for evaluating the overall heat transfer co-efficient (U-value) of masonry wall panel. The conventional burnt clay bricks were collected from the local market,

![Fig. 9. (a),(b),(c),(d) SEM images of Bottom ash under different magnifications.](image)

![Fig. 10. (a),(b) SEM images of Sand under different magnifications.](image)
and the brick wall panel of 125 mm thickness and of size 480 mm * 480 mm was constructed with masonry mortar within wooden frame size of 500 mm * 500 mm. Two sets of such panels with identical bricks, Portland pozzolana cement (PPC), sand, flyash etc. were constructed named as Set-1 and Set-2. In Set-1, mortar mix composition was PPC + 50% Sand and 50% Flyash combination mortar in 1:4 proportion (C-5 mix under Table 5 of MM5 Grade). The same mix was adopted for 12 mm thick plastering on both sides of wall panel, and after subsequent curing, 2 mm (approx.) white putty for evenness of the surface and two coats of acrylic paints were applied. Same steps were followed for construction of Set-2 panel with 100% sand combination (Control mix under Table 5 of MM5 Grade). The putty and two coats of acrylic paints had been applied to create an identical actual scenario of building wall surface, wherein the putty and paints both form some impervious blanket against moisture penetration by sealing the surface pores up to certain extent.

### Table 4. Gradual replacement proportion of Sand by Fly ash and Bottom ash (separately) for MM3 Grade Mortar mix.

| Mortar Mix Identity | Mortar Mix (MM3 Grade) | Cement Wt. ratio | Sand Wt. ratio | Flyash Wt. ratio | Bottom ash Wt. ratio |
|---------------------|-------------------------|------------------|----------------|------------------|----------------------|
| Control             | 1Cement: 6 (100% Sand)  | 1.00             | 6.00           | -                | -                    |
| A-1                 | 1Cement: 6 (90% Sand + 10% Fly ash) | 1.00 | 5.40 | 0.60 | - |
| A-2                 | 1Cement: 6 (80% Sand + 20% Flyash) | 1.00 | 4.80 | 1.20 | - |
| A-3                 | 1Cement: 6 (70% Sand + 30% Flyash) | 1.00 | 4.20 | 1.80 | - |
| A-4                 | 1Cement: 6 (60% Sand + 40% Flyash) | 1.00 | 3.60 | 2.40 | - |
| A-5                 | 1Cement: 6 (50% Sand + 50% Flyash) | 1.00 | 3.00 | 3.00 | - |
| A-6                 | 1Cement: 6 (40% Sand + 60% Flyash) | 1.00 | 2.40 | 3.60 | - |
| A-7                 | 1Cement: 6 (30% Sand + 70% Flyash) | 1.00 | 1.80 | 4.20 | - |
| A-8                 | 1Cement: 6 (20% Sand + 80% Flyash) | 1.00 | 1.20 | 4.80 | - |
| A-9                 | 1Cement: 6 (10% Sand + 90% Fly ash) | 1.00 | 0.60 | 5.40 | - |
| A-10                | 1Cement: 6 (100% Fly ash) | 1.00 | 0.00 | 6.00 | - |
| B-1                 | 1Cement: 6 (90% Sand + 10% Bottom ash) | 1.00 | 5.40 | - | 0.60 |
| B-2                 | 1Cement: 6 (80% Sand + 20% Bottom ash) | 1.00 | 4.80 | - | 1.20 |
| B-3                 | 1Cement: 6 (70% Sand + 30% Bottom ash) | 1.00 | 4.20 | - | 1.80 |
| B-4                 | 1Cement: 6 (60% Sand + 40% Bottom ash) | 1.00 | 3.60 | - | 2.40 |
| B-5                 | 1Cement: 6 (50% Sand + 50% Bottom ash) | 1.00 | 3.00 | - | 3.00 |
| B-6                 | 1Cement: 6 (40% Sand + 60% Bottom ash) | 1.00 | 2.40 | - | 3.60 |
| B-7                 | 1Cement: 6 (30% Sand + 70% Bottom ash) | 1.00 | 1.80 | - | 4.20 |
| B-8                 | 1Cement: 6 (20% Sand + 80% Bottom ash) | 1.00 | 1.20 | - | 4.80 |
| B-9                 | 1Cement: 6 (10% Sand + 90% Bottom ash) | 1.00 | 0.60 | - | 5.40 |
| B-10                | 1Cement: 6 (100% Bottom ash) | 1.00 | 0.00 | - | 6.00 |
2.1.3. Testing of samples

Compressive strength test was performed on 50 mm * 50 mm * 50 mm mortar cubes at 28 days age. Due to pozzolanic action, strength is generally found to be increasing for fly ash and bottom ash blended concrete and mortar beyond 28 days maturity period. Since the acceptable limit for strength was fixed at 28 days maturity as per IS 2250, the same was followed in this work.

Apparent porosity and bulk density samples were tested as per IS 1528 (Part-VIII) Specification. Thermal conductivity test was performed on 50 mm * 50 mm * 12 mm samples, and evaluated in accordance with ISO 22007-2 (2008). Table 8 shows the results of compressive strength at the age of 28 days, thermal conductivity, apparent porosity and bulk densities of MM3 grade mortar samples. The Hot Disc Transient Plane Source thermal conductivity test set up with samples are shown in Fig. 11.

Table 5. Gradual replacement proportion of Sand by Fly ash and Bottom ash (separately) for MM5 Grade Mortar mix.

| Mortar Mix Identity | Mortar Mix (MM5 Grade) | Cement Wt. ratio | Sand Wt. ratio | Fly ash Wt. ratio | Bottom ash Wt. ratio |
|---------------------|------------------------|------------------|----------------|------------------|--------------------|
| Control             | 1Cement: 4 (100% Sand) | 1.00             | 4.00           | -                | -                  |
| C-1                 | 1Cement: 4 (90% Sand + 10% Fly ash) | 1.00 | 3.60 | 0.40 | - |
| C-2                 | 1Cement: 4 (80% Sand + 20% Fly ash) | 1.00 | 3.20 | 0.80 | - |
| C-3                 | 1Cement: 4 (70% Sand + 30% Fly ash) | 1.00 | 2.80 | 1.20 | - |
| C-4                 | 1Cement: 4 (60% Sand + 40% Fly ash) | 1.00 | 2.40 | 1.60 | - |
| C-5                 | 1Cement: 4 (50% Sand + 50% Fly ash) | 1.00 | 2.00 | 2.00 | - |
| C-6                 | 1Cement: 4 (40% Sand + 60% Fly ash) | 1.00 | 1.60 | 2.40 | - |
| C-7                 | 1Cement: 4 (30% Sand + 70% Fly ash) | 1.00 | 1.20 | 2.80 | - |
| C-8                 | 1Cement: 4 (20% Sand + 80% Fly ash) | 1.00 | 0.80 | 3.20 | - |
| C-9                 | 1Cement: 4 (10% Sand + 90% Fly ash) | 1.00 | 0.40 | 3.60 | - |
| C-10                | 1Cement: 4 (100% Fly ash) | 1.00 | 0.00 | 4.00 | - |
| D-1                 | 1Cement: 4 (90% Sand + 10% Bottom ash) | 1.00 | 3.60 | - | 0.40 |
| D-2                 | 1Cement: 4 (80% Sand + 20% Bottom ash) | 1.00 | 3.20 | - | 0.80 |
| D-3                 | 1Cement: 4 (70% Sand + 30% Bottom ash) | 1.00 | 2.80 | - | 1.20 |
| D-4                 | 1Cement: 4 (60% Sand + 40% Bottom ash) | 1.00 | 2.40 | - | 1.60 |
| D-5                 | 1Cement: 4 (50% Sand + 50% Bottom ash) | 1.00 | 2.00 | - | 2.00 |
| D-6                 | 1Cement: 4 (40% Sand + 60% Bottom ash) | 1.00 | 1.60 | - | 2.40 |
| D-7                 | 1Cement: 4 (30% Sand + 70% Bottom ash) | 1.00 | 1.20 | - | 2.80 |
| D-8                 | 1Cement: 4 (20% Sand + 80% Bottom ash) | 1.00 | 0.80 | - | 3.20 |
| D-9                 | 1Cement: 4 (10% Sand + 90% Bottom ash) | 1.00 | 0.40 | - | 3.60 |
| D-10                | 1Cement: 4 (100% Bottom ash) | 1.00 | 0.00 | - | 4.00 |
The U-value test was performed under Guarded Hot Box test facility conforming BS EN ISO 8990 (1996). The U-value test specimen preparation, installing the same in the guarded hot box with sensors on test surface, and the overall test facility with data recording arrangements shown in Figs. 12 and 13 respectively.

### Table 6. Total replacement proportions of Sand by Fly ash and Bottom ash (separately) in association with natural mineral (lime dust) and another industrial residue (marble dust) combination mix for MM3 Grade Mortar.

| Mortar Mix Identity | Mortar Mix (MM3 Grade) | Cement Wt. ratio | Sand Wt. ratio | Flyash Wt. ratio | Bottomash Wt. ratio | Lime dust Wt. ratio | Marble dust Wt. ratio |
|---------------------|------------------------|------------------|----------------|------------------|---------------------|---------------------|-----------------------|
| 1                   | 1Cement: 6 (100% Sand) | 1.00             | 6.00           | -                | -                   | -                   | -                     |
| 2                   | 1Cement: 6 (50% Lime dust +50% Fly ash) | 1.00 | - | 3.00 | - | 3.00 | - |
| 3                   | 1Cement: 6 (50% Marble dust + 50% Fly ash) | 1.00 | - | 3.00 | - | - | 3.00 |
| 4                   | 1Cement: 6 (100% Flyash) | 1.00 | - | 6.00 | - | - | - |
| 5                   | 1Cement: 6 (50% Lime dust + 50% Bottom ash) | 1.00 | - | - | 3.00 | 3.00 | - |
| 6                   | 1Cement: 6 (50% Marble dust + 50% Bottom ash) | 1.00 | - | - | 3.00 | - | 3.00 |
| 7                   | 1Cement: 6 (100% Bottom ash) | 1.00 | - | - | 6.00 | - | - |

### Table 7. Total replacement proportions of Sand by Fly ash and Bottom ash (separately) in association with natural mineral (lime dust) and another industrial residue (marble dust) combination mix for MM5 Grade Mortar.

| Mortar Mix Identity | Mortar Mix (MM5 Grade) | Cement Wt. ratio | Sand Wt. ratio | Fly ash Wt. ratio | Bottom ash Wt. ratio | Lime dust Wt. ratio | Marble dust Wt. ratio |
|---------------------|------------------------|------------------|----------------|------------------|---------------------|---------------------|-----------------------|
| 8                   | 1Cement: 4 (100% Sand) | 1.00             | 4.00           | -                | -                   | -                   | -                     |
| 9                   | 1Cement: 4 (50% Lime dust + 50% Fly ash) | 1.00 | - | 2.00 | - | 2.00 | - |
| 10                  | 1Cement: 4 (50% Marble dust + 50% Fly ash) | 1.00 | - | 3.00 | - | - | 2.00 |
| 11                  | 1Cement: 4 (100% Fly ash) | 1.00 | - | 4.00 | - | - | - |
| 12                  | 1Cement: 4 (50% Lime dust + 50% Bottom ash) | 1.00 | - | - | 2.00 | 2.00 | - |
| 13                  | 1Cement: 4 (50% Marble dust + 50% Bottom ash) | 1.00 | - | - | 2.00 | - | 2.00 |
| 14                  | 1Cement: 4 (100% Bottom ash) | 1.00 | - | - | 4.00 | - | - |

3. Results and discussion

All the test results of fly ash and bottom ash substituted mortar mixes are presented in tabular form under Table Nos. 8, 9, 10 and 11. The compressive strength, thermal
conductivity, apparent porosity and bulk density values are reflected therein. The compliance to minimum grade of mortar as per IS Code has also been indicated.

### Table 8. 28 days Compressive Strength, Thermal Conductivity, Apparent Porosity and Bulk Density values of test specimens for MM3 grade mortar mixes (gradual sand substitution by flyash and bottomash separately).

| Mix Identity | Compressive Strength | Thermal Conductivity | Apparent Porosity | Bulk Density | Minimum Mortar Grade from Load bearing and Durability consideration | Compliance Status |
|--------------|----------------------|----------------------|-------------------|--------------|---------------------------------------------------------------------|-------------------|
| Control      | 3.92                 | 1.5890               | 23.33            | 1.933        | >MM0.7                                                              | MM3 Complied      |
| A-1          | 5.91                 | 0.9017               | 26.666           | 1.967        | ..                                                                  | MM3 Complied      |
| A-2          | 5.84                 | 0.8574               | 22.580           | 1.935        | ..                                                                  | MM3 Complied      |
| A-3          | 5.30                 | 0.6977               | 25.806           | 1.645        | ..                                                                  | MM3 Complied      |
| A-4          | 4.35                 | 0.6505               | 28.125           | 1.594        | ..                                                                  | MM3 Complied      |
| A-5          | 3.26                 | 0.5254               | 32.258           | 1.548        | ..                                                                  | MM3 Complied      |
| A-6          | 3.05                 | 0.4861               | 35.483           | 1.452        | ..                                                                  | MM3 Complied      |
| A-7          | 2.31                 | 0.3786               | 36.363           | 1.182        | ..                                                                  | MM2 Complied      |
| A-8          | 1.69                 | 0.3484               | 37.142           | 1.171        | ..                                                                  | MM1.5Complied     |
| A-9          | 1.16                 | 0.2944               | 37.500           | 1.125        | ..                                                                  | MM0.7Complied     |
| A-10         | 0.68                 | 0.2908               | 38.235           | 1.088        | ..                                                                  | MM0.7Complied     |
| B-1          | 3.19                 | 0.8917               | 25.806           | 1.871        | ..                                                                  | MM3 Complied      |
| B-2          | 2.92                 | 0.7272               | 26.470           | 1.588        | ..                                                                  | MM2 Complied      |
| B-3          | 2.45                 | 0.5602               | 29.411           | 1.471        | ..                                                                  | MM2 Complied      |
| B-4          | 2.17                 | 0.5681               | 30.555           | 1.389        | ..                                                                  | MM2 Complied      |
| B-5          | 1.70                 | 0.5092               | 31.250           | 1.313        | ..                                                                  | MM1.5Complied     |
| B-6          | 1.22                 | 0.4341               | 31.250           | 1.281        | ..                                                                  | MM0.7Complied     |
| B-7          | 1.22                 | 0.4058               | 31.428           | 1.143        | ..                                                                  | MM0.7Complied     |
| B-8          | 1.02                 | 0.3247               | 32.432           | 1.027        | ..                                                                  | MM0.7Complied     |
| B-9          | 0.95                 | 0.2919               | 31.428           | 1.029        | ..                                                                  | MM0.7Complied     |
| B-10         | 0.75                 | 0.2876               | 31.428           | 1.000        | ..                                                                  | MM0.7Complied     |

3.1. Influence of mortar mix proportion on compressive strength

The 28 days compressive strength of control mix with conventional sand-cement combination under MM3 grade (1:6) have been compared with fly ash substituted mixes (A-1 to A-10) (**Table 8 and Fig. 14**). It may be observed that initially with 10% substitution ratio (SR) of fly ash to sand, the compressive strength increased beyond the control mix value, then started decreasing with increasing SR, i.e. 20%, 30%,... and so on. Up to 60% SR, the MM3 grade strength was maintained, and thereafter, the grades were gradually started reducing, and finally attained
MM0.7 grade at 100% SR. The result complied IS 2250 (1981) provisions for maintaining durability and load bearing considerations for masonry mortar for external application. In case of bottom ash substituted mix (B-1 to B-10), the MM3 grade strength could be maintained at 10% SR only, and thereafter reduced gradually to MM0.7 at 100% SR (Table 8 and Fig. 14). For sand less mortar with fly ash and bottom ash (2–7) of MM3 grade, fly ash — Lime dust and bottom ash — lime dust combinations could achieve the grade strength, but combination with marble dust fell short of that grade (Table 9 and Fig. 15). Considering MM5 grade mortar (1:4), the 28 days compressive strength values for fly ash and bottom ash (C-1 to C-10 and D-1 to D-10) substituted mixes, the required grade strength could be maintained up to 50% SR, and thereafter reduced gradually (Table 10 and Fig. 16). Similarly for

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**Fig. 11.** Hot disc transient plane source measurement test set up, while plaster sample test was under preparation.

**Fig. 12.** 125 mm thick burnt clay brick wall panel with both side plaster (a) under preparation for U-value measurement test, and (b) subsequently installed within Guarded Hot Box test facility.
**Fig. 13.** Calibrated Guarded Hot Box Test facility with Instrumentation arrangement for U-value test.

**Fig. 14.** Compressive Strength test values for MM3 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series A and that by Bottom ash in Series B).
sand less mortar with fly ash and bottom ash (9–14) of MM5 grade, fly ash-lime dust and bottom ash-lime dust combinations satisfied the grade strength criteria, but the same with marble dust combinations could reach MM3 equivalent strength only (Table 11 and Fig. 17). With respect to the MM3 grade of mortar test results, the

![Fig. 15. Compressive Strength test values for MM3 Grade Mortar mixes (Total replacement of Sand by Fly ash and Bottom ash with Lime dust and Marble dust).](https://doi.org/10.1016/j.heliyon.2018.e00934)

Table 9. 28 days Compressive Strength, Thermal Conductivity, Apparent Porosity and Bulk Density values of test specimens for MM3 grade mortar mixes for total sand substitution by flyash and bottomash (separately) in association with natural mineral (lime dust) and another industrial residue (marble dust) combination.

| Mix Identity | Compressive Strength | Thermal Conductivity | Apparent Porosity | Bulk Density | Minimum Mortar Grade | Compliance Status |
|--------------|----------------------|----------------------|-------------------|--------------|----------------------|-------------------|
| 1            | 3.92                 | 1.5890               | 23.333            | 1.933        | >MM0.7               | MM3 Complied      |
| 2            | 3.59                 | 0.6860               | 22.222            | 1.667        | ,,                   | MM3 Complied      |
| 3            | 2.31                 | 0.4800               | 31.578            | 1.132        | ,,                   | MM2 Complied      |
| 4            | 0.93                 | 0.3460               | 30.769            | 1.059        | ,,                   | MM0.7 Complied    |
| 5            | 3.49                 | 0.6760               | 23.529            | 1.735        | ,,                   | MM3 Complied      |
| 6            | 2.65                 | 0.5780               | 34.482            | 1.448        | ,,                   | MM2 Complied      |
| 7            | 0.90                 | 0.3250               | 31.250            | 1.037        | ,,                   | MM0.7 Complied    |
From the XRD phase analysis, SEM images, particle size distribution and sp. gravity value of fly ash, it may be observed that flyash particles are glassy spherical shaped, whereas sand particles are angular and fly ash is lighter by around 9% than sand. The mix becomes less closely packed, though the workability of the mix will increase due to glassy spherical shape. For bottom ash particles, though the sizes are bigger than fly ash, but much lighter (15.7%) than sand, and irregular shaped, creating more

Table 10. 28 days Compressive Strength, Thermal Conductivity, Apparent Porosity and Bulk Density values of test specimens for MM5 grade mortar mixes (gradual sand substitution by flyash and bottomash separately).

| Mix Identity | Compressive Strength | Thermal Conductivity | Apparent Porosity | Bulk Density | Minimum Mortar Grade MM0.7 from Load bearing and Durability consideration | Compliance Status |
|--------------|----------------------|----------------------|-------------------|--------------|--------------------------------------------------------------------------|------------------|
| Control      | 10.06                | 1.1980               | 24.242            | 1.970        | >MM0.7                                                                   | MM5 Complied     |
| C-1          | 11.96                | 1.1030               | 25.000            | 1.650        | ,,                                                                       | MM5 Complied     |
| C-2          | 9.45                 | 0.9014               | 26.470            | 1.676        | ,,                                                                       | MM5 Complied     |
| C-3          | 8.56                 | 0.8008               | 27.777            | 1.667        | ,,                                                                       | MM5 Complied     |
| C-4          | 6.80                 | 0.6509               | 30.303            | 1.606        | ,,                                                                       | MM5 Complied     |
| C-5          | 5.71                 | 0.6073               | 33.333            | 1.606        | ,,                                                                       | MM5 Complied     |
| C-6          | 3.81                 | 0.5517               | 33.333            | 1.533        | ,,                                                                       | MM3 Complied     |
| C-7          | 2.31                 | 0.3874               | 38.709            | 1.484        | ,,                                                                       | MM2 Complied     |
| C-8          | 1.09                 | 0.3746               | 40.625            | 1.250        | ,,                                                                       | MM0.7Complied    |
| C-9          | 0.95                 | 0.3509               | 41.935            | 1.258        | ,,                                                                       | MM0.7Complied    |
| C-10         | 0.88                 | 0.3222               | 43.750            | 1.188        | ,,                                                                       | MM0.7Complied    |
| D-1          | 7.20                 | 1.1070               | 26.666            | 1.833        | ,,                                                                       | MM5 Complied     |
| D-2          | 6.52                 | 0.8861               | 29.032            | 1.742        | ,,                                                                       | MM5 Complied     |
| D-3          | 5.91                 | 0.6936               | 33.333            | 1.667        | ,,                                                                       | MM5 Complied     |
| D-4          | 5.84                 | 0.6171               | 33.333            | 1.600        | ,,                                                                       | MM5 Complied     |
| D-5          | 5.16                 | 0.5673               | 34.482            | 1.448        | ,,                                                                       | MM5 Complied     |
| D-6          | 4.62                 | 0.4802               | 35.294            | 1.324        | ,,                                                                       | MM3 Complied     |
| D-7          | 3.94                 | 0.4285               | 39.393            | 1.212        | ,,                                                                       | MM3 Complied     |
| D-8          | 3.33                 | 0.3644               | 39.393            | 1.152        | ,,                                                                       | MM3 Complied     |
| D-9          | 2.85                 | 0.3295               | 40.000            | 1.086        | ,,                                                                       | MM2 Complied     |
| D-10         | 2.72                 | 0.2812               | 42.424            | 1.091        | ,,                                                                       | MM2 Complied     |

standard deviation (sd) was calculated. The sd observed to vary between 0.0417 (minimum) to 0.1445 (maximum), and the corresponding co-efficient of variation found to be 1.3072 and 12.4569 respectively. For MM5 grade mortar sd values varied between 0.0292 (minimum) to 0.8372 (maximum) and the corresponding co-efficient of variation found to be 3.3182 and 12.8405 respectively.
Fig. 16. Compressive Strength test values for MM5 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series C and that by Bottom ash in Series D).

Table 11. 28 days Compressive Strength, Thermal Conductivity, Apparent Porosity and Bulk Density values of test specimens for MM5 grade mortar mixes for total sand substitution by flyash and bottomash (separately) in association with natural mineral (lime dust) and another industrial residue (marble dust) combination.

| Mix Identity | Compressive Strength | Thermal Conductivity | Apparent Porosity | Bulk Density | Minimum Mortar Grade MM0.7 from Load bearing and Durability consideration | Compliance Status |
|--------------|----------------------|----------------------|-------------------|--------------|------------------------------------------------------------------------|------------------|
| 8            | 10.06                | 1.1980               | 24.242            | 1.970        | >MM0.7                                                                | MM5 Complied     |
| 9            | 5.670                | 0.485                | 19.444            | 1.805        | ,,                                                                   | MM5 Complied     |
| 10           | 3.220                | 0.542                | 15.868            | 1.324        | ,,                                                                   | MM3 Complied     |
| 11           | 0.900                | 0.427                | 30.769            | 1.410        | ,,                                                                   | MM0.7Complied    |
| 12           | 6.760                | 0.485                | 26.666            | 2.033        | ,,                                                                   | MM5 Complied     |
| 13           | 3.740                | 0.486                | 20.000            | 2.133        | ,,                                                                   | MM3 Complied     |
| 14           | 0.900                | 0.401                | 25.675            | 1.473        | ,,                                                                   | MM0.7Complied    |
More the substitution ratio, more the void content, and less the density, which are evident from Figs. 18, 19, 20 and 21 for different mortar mix combinations, where apparent porosity and bulk density values are plotted. Therefore, it can be summarized that reasons for reduction in compressive strength with increasing substitution ratio are — i) increase in porosity, and ii) replacement of dense aggregate with lighter and porous aggregate.

3.2. Influence of mortar mix proportion on thermal conductivity

Under MM3 grade for fly ash substituted mix samples (A-1 to A-10), it was observed that the conductivity values gradually reduced, and at 60% SR (A-6, up to which MM3 grade was maintained) the reduction was 69.4%, and at 100% SR (A-10), the reduction was 81.7% (Table 8 and Fig. 22) Similarly for bottom ash substituted samples (B-1 to B-10), the conductivity value though reduced, but at 10% SR (since MM3 grade strength was maintained up to that level), the reduction was 43.9%, and thereafter it went on reducing till 100% SR (B-10), where the value was reduced by 81.9% (Table 8 and Fig. 22). For fly ash-lime dust (Mix identity 2) and fly ash-marble dust (Mix identity 3) combination mixes, the reductions were 56.8% and 69.8% respectively. For bottom ash-lime dust (Mix identity 5) and bottom ash-marble dust (Mix identity 6) combination mixes, the
Fig. 18. Apparent Porosity and Bulk Density test values for MM3 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series A and that by Bottom ash in Series B).

Fig. 19. Apparent Porosity and Bulk Density test values for MM5 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series C and that by Bottom ash in Series D).
Fig. 20. Apparent Porosity and Bulk Density test values for MM3 Grade Mortar mixes (Total replacement of Sand by Fly ash and Bottom ash with lime dust and marble dust).

Fig. 21. Apparent Porosity and Bulk Density test values for MM5 Grade Mortar mixes (Total replacement of Sand by Fly ash and Bottom ash with Lime dust and marble dust).
Fig. 22. Thermal Conductivity test values for MM3 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series A and that by Bottom ash in Series B).

Fig. 23. Thermal Conductivity test values for MM3 Grade Mortar mixes (Total replacement of Sand by Fly ash and Bottom ash with Lime dust and Marble dust).
thermal conductivity value reductions were 57.4% and 63.6% respectively (Table 9 and Fig. 23).

Considering MM5 grade for fly ash (C-1 to C-10) and bottom ash (D-1 to D-10) substituted samples, at 50% SR (C-5 and D-5), the corresponding reductions in thermal conductivity values w.r.t. the control one were 54% and 52.6% respectively. At 100% SR for both the cases (C-10 and D-10), the corresponding reductions were 73.1% and 76.5% respectively (Table 10 and Fig. 24). For the sand less combinations (Mix identities 9,10,12 and 13) in this grade of mortar, the corresponding reductions were 59.5%, 54.7%, 59.5% and 59.4% respectively (Table 11 and Fig. 25). Presence of pore in the mortar contributes to increasing thermal conductivity, since air in pore offers the insulating effect. The absence of dense inner structure due to the shape of flyash and bottomash particles also add to lesser thermal conductance. Further the fused structure of fly ash and bottom ash with mullite and amorphous silica, hematite and anatase (TiO₂) offer lesser conductance than the quartz silica structure of river sand. The standard deviation for thermal conductivity test results for MM3 grade samples varied between 0.00205 (minimum) to 0.02523 (maximum), and the corresponding co-efficient of variation oscillated between 0.6988 and 2.7739 respectively. The same for MM5 grade was found as 7.07E-05 (minimum) to 0.02814 (maximum) and corresponding co-efficient of variation are 0.0189 and 5.6269 respectively.

![Thermal Conductivity test values for MM5 Grade Mortar mixes (Gradual replacement of Sand by Fly ash in Series C and that by Bottom ash in Series D).](https://doi.org/10.1016/j.heliyon.2018.e00934)
3.3. Influence of mortar mix proportion on apparent porosity and bulk density

The apparent porosity and bulk density test results of MM3 Grade, MM5 Grade and Sand-less MM3 Grade and Sand-less MM5 Grade Mortars are shown in Tables 8, 9, 10, and 11 and Figs. 18, 19, 20, and 21 respectively. It may be observed that with the increasing rate of SR for both fly ash and bottom ash substitutions, the corresponding porosity values increased and bulk density values decreased. The reason for such phenomena may purely be attributed to the fused alumina-silicate phase composition of fly ash and bottom ash, and particle shape and sizes of both.

3.4. Influence of mortar mix proportion on overall heat transfer co-efficient value or U-value

From the U-value test with one particular mortar mix of MM5 grade (C-5), it was observed that the reduction in U-value was 15.58% while compared with the conventional mortar mix of same grade (Table 12). Overall heat transfer coefficient of the total assembly is primarily dependent on individual constituent material’s thermal conductivity value, and the corresponding resistance to one dimensional heat flow. The configuration or construction of the assembly also speed up or restrict the heat flow. Due to conductive nature of quartz silica, the mortar mix with ordinary sand has offered least resistance to the flow, whereas the mortar mix with fly ash,
Table 12. Test Results of U-value experiment.

| Item description | Burnt clay brick wall panel of size 480 mm * 480 mm * 125 mm with Mortar Grade (MM5) & Plaster (12 mm thick) made of PPC and 50% Fly ash + 50% Sand combination (1:4) SET - 1 | Burnt clay brick wall panel of size 480 mm * 480 mm * 125 mm with Mortar Grade (MM5) & Plaster (12 mm thick) made of PPC and 100% Sand combination (1:4) SET - 2 |
|------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Test Days with Date | Day 1, 16<sup>th</sup> June 2017 | Day 2, 17<sup>th</sup> June 2017 | Day 3, 21<sup>st</sup> June 2017 | Day 4, 22<sup>nd</sup> June 2017 | Day 5, 23<sup>rd</sup> June 2017 | Day 6, 26<sup>th</sup> June 2017 |
| Area of Surface, A (m<sup>2</sup>) | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Metering Box (MB) Air temperature (°C) | 40.01 | 40.01 | 40.01 | 40.00 | 40.00 | 40.01 |
| Cold Box (CB) Air temperature (°C) | 24.59 | 24.66 | 24.62 | 24.61 | 24.60 | 24.56 |
| Air temperature difference between MB & CB, ΔT (°C) | 15.42 | 15.35 | 15.38 | 15.40 | 15.40 | 15.44 |
| Surround Panel Surface temperature difference (°C) | 15.15 | 15.12 | 15.17 | 15.17 | 15.13 | 15.16 |
| Sample surface temperature difference (°C) | 9.24 | 9.22 | 9.38 | 8.45 | 8.31 | 8.45 |
| Total heat input into MB (A) (Watt) | 19.08 | 18.55 | 18.96 | 21.29 | 20.35 | 20.44 |
| MB Wall loss (B) (Watt) | 1.549 | 1.432 | 1.465 | 1.631 | 1.123 | 1.162 |
| Heat flow from MB to CB (C) = (A)-(B) (Watt) | 17.53 | 17.11 | 17.50 | 19.66 | 19.22 | 19.28 |
| Flanking loss (D) (Watt) | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| Extraneous heat transfer (E) (Watt) | 2.46 | 2.45 | 2.46 | 2.46 | 2.46 | 2.47 |
| Surround Panel heat flow (F) (Watt) | 3.96 | 3.96 | 3.97 | 3.97 | 3.96 | 3.97 |
| Sample heat flow(G) = (C)-(D)-(E)-(F) Watt | 10.84 | 10.45 | 10.81 | 12.97 | 12.54 | 12.58 |
| U value = (G)/A* ΔT (W/m<sup>2</sup>°C) | 3.051 | 2.954 | 3.050 | 3.655 | 3.534 | 3.536 |
| Avg. U value in each Set (W/m<sup>2</sup>°C) | 3.018 | 3.575 |
| Difference in U value (%) | 15.58 |
which possess lesser conductivity value, due to its constituent phase, shape and structures offered higher resistance to the heat flow, and therefore the difference in U-value resulted.

4. Conclusions

Building sector is one of the major energy consumer and the spiralling incremental increase need to be curbed by way of energy efficient construction. Energy consumption due to cooling/heating requirement may be effectively controlled by efficient envelop design with low embodied constituent materials.

This paper investigates the possibility of substituting sand with fly ash and bottom ash in mortar and plaster mix as low thermally conducting materials. Besides, finding the strength adequacy in compliance with relevant IS Code, thermal conductivity parameter also explored. To understand the change in thermal conductivity values with the change in substitution ratios of sand by fly ash and bottom ash (separately), apparent porosity and bulk density values of such mortar mixes were also evaluated. From the study of inherent material properties of sand, fly ash and bottom ash like particle size, grading, shape, specific gravity etc., it could be established that fly ash and bottom ash produced mortar mix with lesser bulk density and more apparent porosity, than those compared with conventional mortar mix with sand. The lower density value of mortar mix is advantageous for reduced dead load of the whole envelop assembly. From the durability point of view as per Code provision, even the mix with 100% sand substitution complied with minimum grade of mortar MM0.7. Further, from the test result it is also revealed that up to 60% substitution by fly ash, MM3 and MM5 grades of mortar could be produced. The reduction in thermal conductivity values for 100% substitution by fly ash alone for MM3 and MM5 grade mortars are found to be around 82% and 73% respectively. For 100% bottom ash substitution, those values are 68% and 75% respectively. The overall heat transfer co-efficient U-value of brick wall panel with 50% fly ash substituted mortar mix was found to be lesser by 15.58%, while compared with identical panel with conventional mix with sand. Therefore, building envelop made with such ash blended mix can be considered as energy efficient, since due to lesser heat transmission inside, cooling/heating demand by the building will be reduced. The important outcome from this work has been a way of effective utilization of thermal power plant ash towards energy efficient building envelop construction without any specialized technique or addition of chemical etc.. Simultaneously, the ecological disturbances caused due to fast depletion of river sand, shall be minimized with such coal ash substitution.

There remains future scope for this work to be extended with incorporation of some additional waste material(s) in addition to the coal ash varieties, to further enhance the insulating effect of the mix under lower embodied energy scenario.
Declarations

Author contribution statement

Avijit Ghosh: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Arup Ghosh: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Subhasis Neogi: Performed the experiments; Analyzed and interpreted the data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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