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RESEARCH PAPER

Experimental Study on Hardened Mechanical and Durability Properties of Industrial Ash Bricks

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Abstract
Bricks are one of the popular construction materials since olden days and are used for a variety of applications such as load bearing and non-load bearing walls, piers, bridges, bunkers and so on. Vast tracts of fertile soil are turned into wastelands due to mining of clay for the manufacture of clay bricks and fuel wood required for brick kilns becomes depleted, scarce and costlier. Coal-based thermal power plants contribute to about 50% of the total electricity produced in India. In doing so, they generate large volume of coal ash (pond ash and fly ash). The safe disposal of coal ash requires vast land area. To overcome the environmental hazards created by the production of clay bricks and coal ash from thermal power plants, effective utilization of coal ash replacing natural clay in brick making is studied. In this present paper study, an attempt has been made to find out the optimum proportion of pond ash in brick manufacturing. The research work covers a wide range starting from studying the properties and influence of pond ash at the microstructure level to the behaviour of industrial bricks (I-ash) units. The I-ash bricks made with incorporation of pond ash were studied for specific brick properties. Durability tests studies were also conducted to study the feasibility of using I-ash bricks in construction.

Keywords Industrial Ash Brick · Sorptivity · Abrasion · Water absorption · Scanning electron microscopy images · Energy dispersive spectroscopy

1 Introduction

Clay brick masonry is a popular non-engineered construction throughout India and in developing countries. Burnt clay bricks have better durability, strength and reliability and are readily available. India consumes about 180 billion tonnes of bricks, exhausting approximately 340 billion tonnes of clay every year, and due to these vast tracts of land covered with fertile soil are turned into wastelands. In recent years, growing awareness on environmental impact of using fertile top soil for brick manufacturing has prompted the search for alternative systems of masonry units. The factors like economics involved in the usage of manpower for the production of clay bricks and the fuel required for the brick kilns becoming scarce and costlier have forced the industry to adopt cheaper alternative materials for brick making. In India, more than 50% of the total electricity generated is contributed by coal-based thermal power plants. The ash generated by burning of coal in thermal power stations amounts to approximately 150 million tonnes per annum. The storage and disposal of coal ash require vast land area and create environmental hazards. Because of the initiatives taken in India to promote reusing of thermal power plant waste material, fly ash and pond ash are effectively used in making bricks as an alternative to clay in bricks. Detailed experimental studies were conducted to understand the characteristics of I-ash brick units and durability performance of the I-ash bricks.

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2 Literature Review

Lihuva Zhu and Zengmei Zhu (15) explored on the potential of clay brick waste as a partial replacement of cement and aggregate. The mechanical and durability properties were investigated in mortar and concrete and the suitability of the recycled clay brick was determined. Muhammad Ekhlasur Rahmam et al. (2018) experimented on the investing the performance characteristics of bricks by replacing cement partially using fly ash and palm oil fuel ash. The bricks satisfied the ASTM standards and had good compressive strength. Thermogravimetric analysis was performed and it was revealed that calcium hydroxide formed had gradually decreased due to increase in pozzolanic content. Safeer Abbas et al. (1) investigated the utilization of fly ash as a partial replacement for clay in traditional clay bricks. The optimal replacement level for Fly ash was found as 20%. The fly ash bricks were found to have less efflorescence, good compressive strength and less self-weight. Vidhya and Kandasamy (14) conducted an experiment on coal ash brick units. It was concluded that the pond ash and fly ash mix combinations performed well in mechanical and durability performance of the coal ash bricks. Bhangale and Nemade (4) conducted a case study on replacement of fine aggregate by pond ash in cement concrete. Concrete produced with the replacement of fine aggregate by 20% of pond ash mix shows higher compressive strength at various days of curing and weight density of concrete got decreased with increase in pond ash percentage. Vidhya et al. (13) investigated the microstructure and mechanical properties of pond ash brick. The density, water absorption and sorptivity values of pond ash brick got reduced with increase in percentage of pond ash. Bang et al. (3) investigated the utilization of pond ash as a fine aggregate and determined the strength characteristics of concrete made with pond ash, natural sand and crusher sand. The compressive strength, flexural strength and split tensile strength of concrete were higher with 25% of pond ash content with both natural sand and crusher sand. Freeda Christy and Tensing (5) conducted experiments on fly ash bricks and conventional bricks. The compressive strength of fly ash bricks was 40 to 80% higher than that of conventional clay bricks and the weight density of fly ash brick was 10% lighter than conventional clay brick. Akhtar et al. (2) studied the properties of bricks with total replacement of clay by fly ash mixed with different materials. Three categories of bricks namely plain fly ash brick (FAB), treated fly ash brick (TFAB) and treated fly ash stone dust brick (TFASDB) were studied. Treated fly ash stone dust bricks 10TFASDB and 25TFASDB showed higher compressive strength values of 7.16 MPa and 7.9 MPa, respectively. Hakan (7) conducted toxic elements leachability tests on lightweight fly ash bricks by TCLP and ASTM methods. The results of the leachability test are as follows: Fe, Zn and Mn were detected in the leachate obtained from the test run with the whole brick pieces using TCLP method. But their solubility levels were in compliance with the drinking water standards except Mn concentration which was not in conformity as per the norms of the Turkish Standards Institute (TSE).

3 Experimental Investigation

Experimental investigation was carried out to determine the mechanical properties and durability performance of brick units. Totally, 360 industrial ash brick specimens of size 230 × 110 × 75 mm were cast for experimental study to determine the compressive strength, water absorption, weight density, efflorescence, hardness, initial rate of absorption (IRA) and sorptivity of coal ash bricks. Durability indicators such as resistance to chemical attack were also studied using 398 brick specimens. Tests to determine the fundamental strength were conducted on the brick specimens. Energy-dispersive X-ray diffraction study (EDS) and scanning electron microscopy (SEM) were also carried out for elemental analysis and to discern the chemical composition of the ingredients of the coal ash bricks.

3.1 Ingredients Used

Pond ash and fly ash procured from Thermal Power Station, India, in a single batch were used for the entire investigation. The test results of fly ash samples are listed in Table 1. Potable water was used for brick manufacturing and curing. Gypsum having purity of 80% was used for this study. Lime, an important constituent in brick, having CaO greater than 20% was used in the preparation of test specimens. Stone dust commonly employed as a filler material was used as an ingredient in the brick manufacturing. The specific gravity of stone dust was 2.65.

3.2 Casting of Brick

The ingredients (pond ash, fly ash, lime, gypsum, stone dust and water) of the brick specimens were taken in appropriate quantities on weight basis and are weighed accordingly. They were mixed uniformly using a pan mixer. The mix was transported to the casting yard through belt conveyor and is

Table 1 Physical properties of fly ash and pond ash

Properties	Fly ash	Pond ash	Requirement of IS 3812: 2003
Specific gravity	2.18	2.12	2.1 – 3.0
Surface area (m^2/kg)	290	265	Minimum 200
Particle size (μm)	10 – 50	10—50	45

pressed in standard brick moulds. The bricks were sprinkle-cured with water for 3 days. After curing, the bricks were dried in open air for more than a week.

3.3 Mix Combinations of I-ash Bricks

Proportioning of raw materials is an important aspect in the making of I-ash bricks of desired quality. The following mix combinations of fly ash, pond ash (P.A), lime, gypsum, sand, stone dust and water in present adopted for making I-ash bricks (IAB) are represented in Table 2.

3.4 Experimental Work and Instrumentation

Basic tests on industrial ash bricks for determination of physical property as weight density and mechanical property as compressive strength were carried out. Durability studies as water absorption, resistance to chemical attack, initial rate of absorption, sorptivity and resistance to abrasion on industrial ash bricks (IAB), fly ash bricks (FAB) and clay bricks (CCB) were carried out. Totally, 360 specimens of brick were cast for the study.

The basic properties of bricks were determined as per IS: 3495:1992—Methods of Tests of Burnt Clay Building Bricks. Resistance offered by Industrial ash brick, fly ash brick and clay brick to chemical attack was studied under various aggressive environments. The brick specimens were cured in potable water with 5% of sodium sulphate and potable water with 5% of sodium chloride and seawater. The bricks were immersed in the respective chemical solutions for various periods of 3, 7, 14, 21, 28, 56 and 90 days. Initial rate of absorption values was used to select the best combination of mortar and brick type to achieve good bonding. Thirty brick specimens were used for initial rate of absorption and sorptivity test. Totally, 408 brick specimens were cast and studied for the determination of the durability properties of the bricks. The wear and tear in brick specimen are also one of the important factors in finding out the level of deterioration in the brick. Abrasion studies were conducted on the fly ash brick and industrial ash brick specimens as per IS 1237:1980—Cement Concrete Flooring Tiles—Specifications. Twenty specimens were cast for the abrasion study. The test specimens of size $70 \times 70 \times 25$ mm are taken. The specimens were placed in the holding device and a load of 300 N is applied at the centre and was put in motion at a speed of 30 revolutions/min. The depth of wear and tear was noted for each direction.

Table 2 Mix combinations of I-ash bricks

Mix ID	Lime	Gypsum	Fly ash	Pond ash	Stone dust
	In percentage of materials				
IAB1	6	5	35	34	20
IAB2	8	5	35	32	20
IAB3	10	5	35	30	20
IAB4	12	5	35	28	20
IAB5	14	5	35	26	20
IAB6	16	5	35	24	20

4 Results and Discussion

The results of the detailed and systematic experimental studies carried out in this research work are presented in this section. The microstructure and element properties of fly ash, pond ash and industrial ash brick powder were studied using SEM, EDS and XRD techniques. The basic properties and durability performance of industrial ash brick, fly ash brick and clay brick are presented and discussed.

4.1 Microstructure of Materials

Scanning electron microscopy (SEM) images and energy-dispersive spectroscopy (EDS) data show the morphology of fly ash, pond ash and industrial ash brick powder.

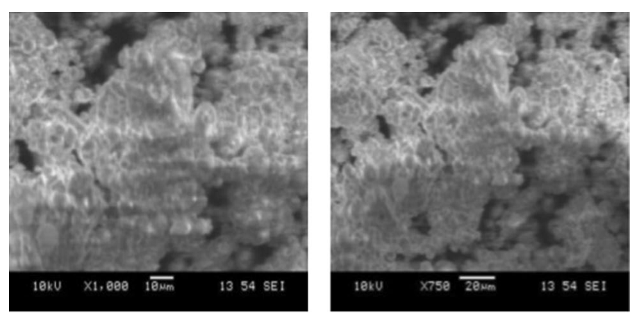

Fig. 1 SEM analysis for fly ash sample

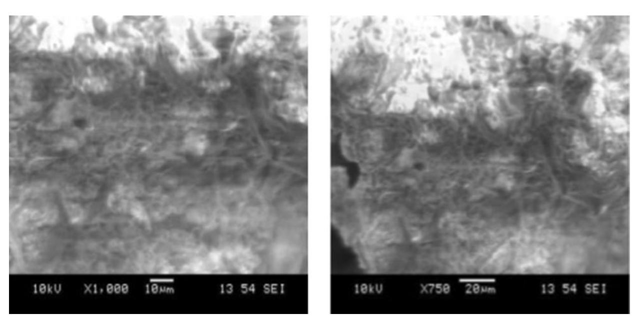

Fig. 2 SEM analysis for pond ash sample

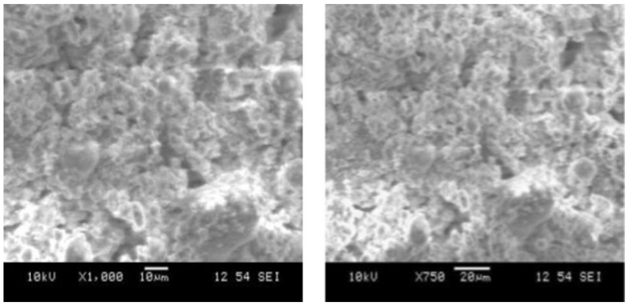

Fig. 3 SEM analysis for industrial ash brick powder sample

Figures 1, 2 and 3 show the texture of the fly ash, pond ash and industrial ash brick powder material.

Figures 1, 2 and 3 illustrate the microstructure of fly ash, pond ash and brick powder as captured through a scanning electron microscope. Majority of the fly ash particles are spherical in shape and present a spongy appearance. Fly ash displays agglomeration of amorphous materials. The particles have a lower pore size. Thus, the microstructure of fly ash is highly inhomogeneous. Pond ash particles are spongy in appearance and brick powder particles are spherical in shape and homogeneous in structure. The particle size of fly ash, pond ash and industrial ash brick powder varies from 10 to 50 µm. The matrix of pond ash exhibits fully closed structure similar to honeycombing. The grains of pond ash are densely packed. The microstructure of the coal ash brick powder presents a less porous structure. Figure 4a, b and c shows the EDS analysis of fly ash, pond ash and industrial ash brick powder materials.

The XRD analysis was used to confirm the crystalline nature of the phases formed during alkali activations. Figure 5a and b shows the XRD analysis of fly ash and pond ash samples.

XRD analysis of fly ash sample is shown in Fig. 5a. Fly ash is essentially a vitreous material. It consists of quartz (SiO_2) and alundum (Al_2O_3) in their crystalline phases. The mass percentage of alundum and quartz is 36.34 and 63.66%, respectively. The characteristic peak in the graph indicates the closely packed framework of atoms and molecules. Figure 5b shows the XRD analysis of pond ash material. The pond ash is a substantial material. It contains a series of minority crystalline phases such as quartz, alundum and FeO. The XRD analysis of the pond ash material reveals that it is spongy and has honeycomb structure. The pond ash consists of spherical metallic particles. The mass percentage of quartz is 64.28%, for alundum it is 34.29% and for FeO it is 1.43%.

Table 3 shows the chemical composition of fly ash, pond ash and coal ash brick powder samples.

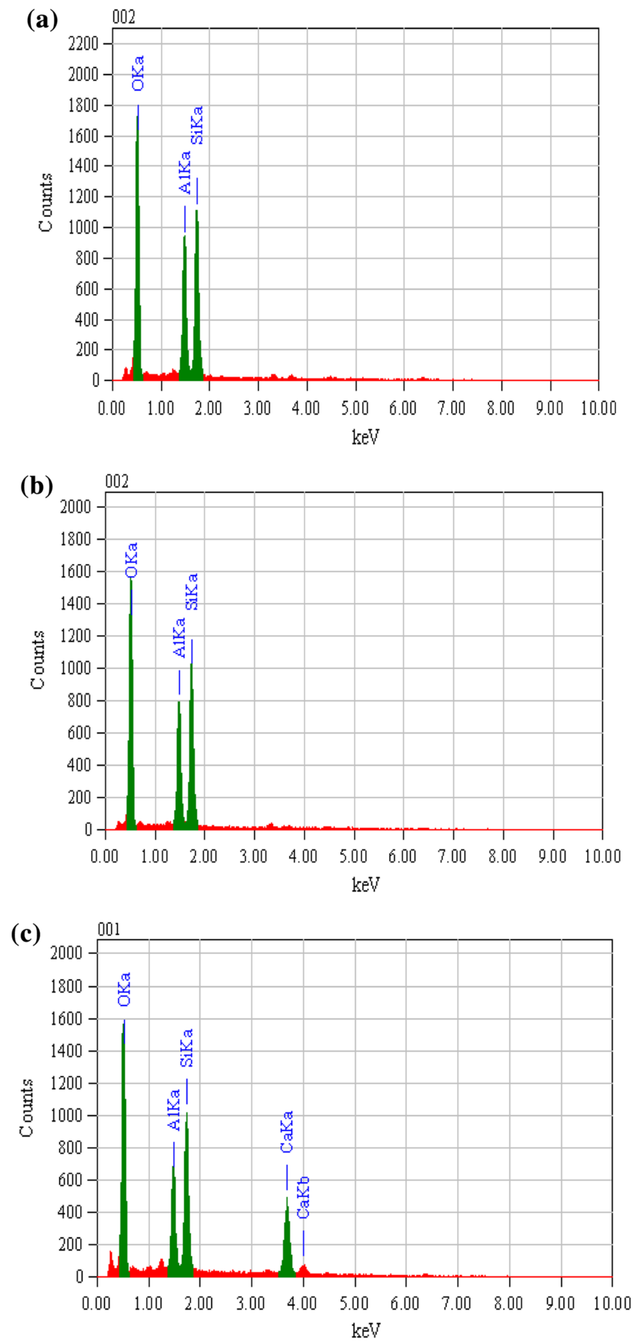

Fig. 4 **a** EDS analysis of Fly ash sample **b** EDS analysis of Pond ash sample **c** EDS analysis of I-ash brick powder sample

In all the three samples, the SiO_2 content is higher than the Al_2O_3 content. Fly ash does not possess CaO. Hence, it belongs to Class F. CaO enhances the compressive strength and it serves as binder of fly ash and pond ash.

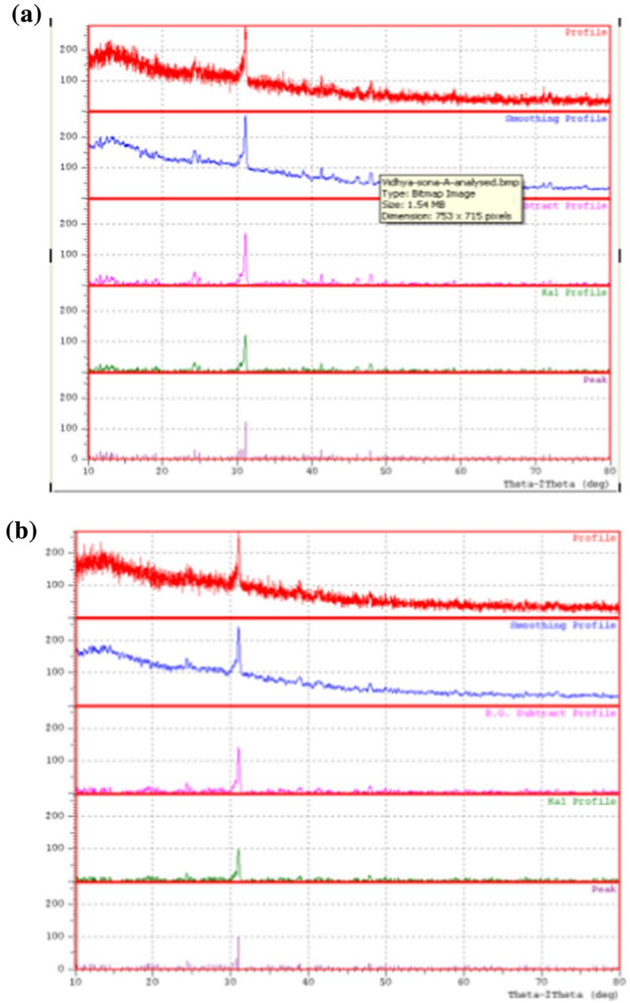

Fig. 5 **a** XRD analysis of Fly ash sample **b** XRD analysis of Pond ash sample

Table 3 Chemical composition of fly ash, pond ash and I-ash brick powder samples

Sample	Fly ash	Pond ash	Coal ash brick powder
Composition	%	%	%
O	50.98	51.01	46.74
Al	19.52	19.23	14.44
Si	29.51	29.76	24.83
Ca	–	–	13.95
SiO_2	63.66	64.28	53.20
Al_2O_3	36.34	34.29	27.28
FeO	–	1.43	–
CaO	–	–	19.52

4.2 Mechanical Properties

Table 4 represents the mechanical properties of the industrial ash bricks. All industrial ash brick samples possessed required compressive strength of 3.5 N/mm^2 as per IS 12894:2002 that was achieved within 14 days of casting. The water absorption values of the industrial ash bricks were in range less than 20% as per IS 3495 (Part 2):1992.

Figure 6 depicts the compressive strength of bricks with respect to age of testing for mix proportions.

It is noted that the water absorption value becomes reduced with increase in pond ash content due to reduction in pores. Since pond ash acts as filler material, increase in pond ash content decreases the water absorption capacity of industrial ash bricks. The water absorption values of all the mix combinations of industrial ash bricks satisfy the codal provision of IS 3495 (Part 2):1992. The water absorption value of the mixes with mix id IAB1, IAB2 and IAB5 is found to be less than 10%.

Figure 7 shows the comparison of weight density for mixes of industrial ash brick specimens with various mix proportions. From Table 4, it is observed that the behaviour of compressive strength with respect to the weight density of brick specimens is directly proportional to all mix proportions.

4.3 Durability Performance of Bricks

4.3.1 Sulphate and Seawater Attack

Table 5 shows the summary of results of clay bricks, coal ash bricks and fly ash bricks subjected to chemical exposure.

After 90 days of immersion in sodium sulphate solution, it is noted that the compressive strength of coal ash bricks is 2.1% higher than that of industrial ash bricks. The clay bricks show a 15% weight gain. The compressive strength of the industrial ash bricks and fly ash bricks gets increased after 28 days of immersion in sodium chloride solution. The compressive strength loss of industrial ash brick is 5.26% lesser than fly ash bricks, after immersion in sodium chloride solution for 90 days. Clay brick shows enhanced resistance against chemical attack (Na_2SO_4, NaCl and seawater) compared to industrial ash brick and fly ash brick.

4.3.2 Initial Rate of absorption (IRA)

Figure 8a, b and c shows the initial rate of absorption values with respect to time for clay brick, industrial ash brick and fly ash brick specimens.

Table 4 Mechanical properties of I-ash bricks

Mix ID	IAB1	IAB2	IAB3	IAB4	IAB5	IAB6
Compressive strength (MPa)	6.4	7.2	7.6	8.2	8.7	9.2
Water absorption (%)	8.10	8.30	8.60	8.65	8.92	9.20
Weight density (kN/m^3)	14.35	14.56	14.78	15.21	15.64	15.72

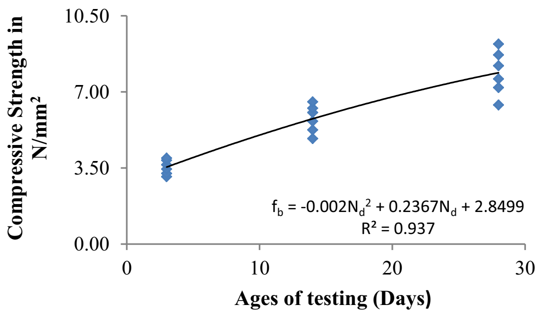

Fig. 6 Compressive strength Vs Age of testing

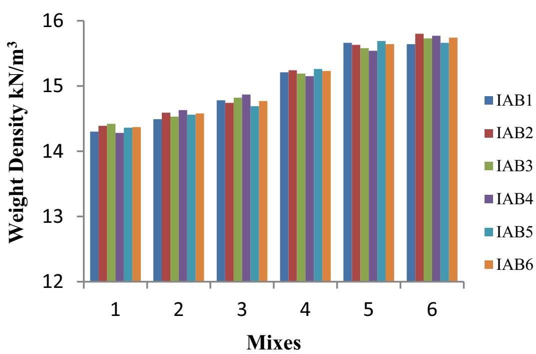

Fig. 7 Comparison of weight density for mixes (IAB1 to IAB5)

From Fig. 8a, b and c, initial rate of absorption values of clay brick, industrial ash brick and fly ash brick is derived using the following equations.

For clay brick, $i = 3.326(t)^{0.5} + 0.824$.

For I-ash brick, $i = 0.893\ (t)^{0.5} + 1.005$.

For fly ash brick, $i = 1.452\ (t)^{0.5} + 0.955$.

Table 6 shows the "up to saturation sorptivity" values of clay brick, fly ash brick and coal ash brick.

Coal ash brick shows 73 and 39% lower sorptivity values than that of clay brick and fly ash brick, respectively. Fly ash brick shows 56% lower sorptivity value than that of conventional clay bricks.

4.3.3 Sorptivity

Figure 9a, b and c shows the typical sorptivity plot (absorption vs time½) for clay brick, I-ash brick and fly ash brick. The clay brick, coal ash brick and fly ash brick became saturated within 60 min, 360 min and 290 min, respectively, during the test and this is shown by the curves' flattening off trend.

The following regression equations have been derived from the graph of absorption values vs. square root of time interval using Microsoft Excel polynomial linear trend line analysis.

Clay brick, $i = -0.365t + 4.977(t)^{0.5}$—0.299.

Industrial ash brick, $i = -0.036t + 1.121(t)^{0.5} + 0.431$.

Fly ash brick, $i = -0.072t + 1.932(t)^{0.5} + 0.477$.

Table 7 shows the consolidated sorptivity values of clay brick, industrial ash brick and fly ash brick. Industrial ash brick shows 78 and 42% lower sorptivity values than clay brick and fly ash brick, respectively.

Industrial ash bricks take longer water absorption time when compared to other types of brick. Microstructure of pond ash material shows fully closed and dense-packed structure; hence, IRA and water absorption are lower compared to clay brick. Sorptivity test describes the absorption capacity of brick units, taking into account the interaction between mortar and brick at critical point. Low sorptivity values show lower porosity of bricks.

4.3.4 Resistance to Abrasion

Table 8 shows the abrasion test values of I-ash specimen and fly ash specimens. Figure 10a and b shows the fly ash specimen and coal ash specimen after abrasion test.

Table 5 Weight gain and strength loss of bricks subjected to chemical exposure

Type of Brick	Sodium sulphate solution		Sodium chloride solution		Sea water	
	Weight gain in %	Strength loss in %	Weight gain in %	Strength loss in %	Weight gain in %	Strength loss in %
CCB	15.00	7.60	14.80	6.50	14.20	8.20
IAB	9.80	14.20	9.70	10.80	8.30	15.20
FAB	10.20	14.50	10.00	11.40	9.40	15.70

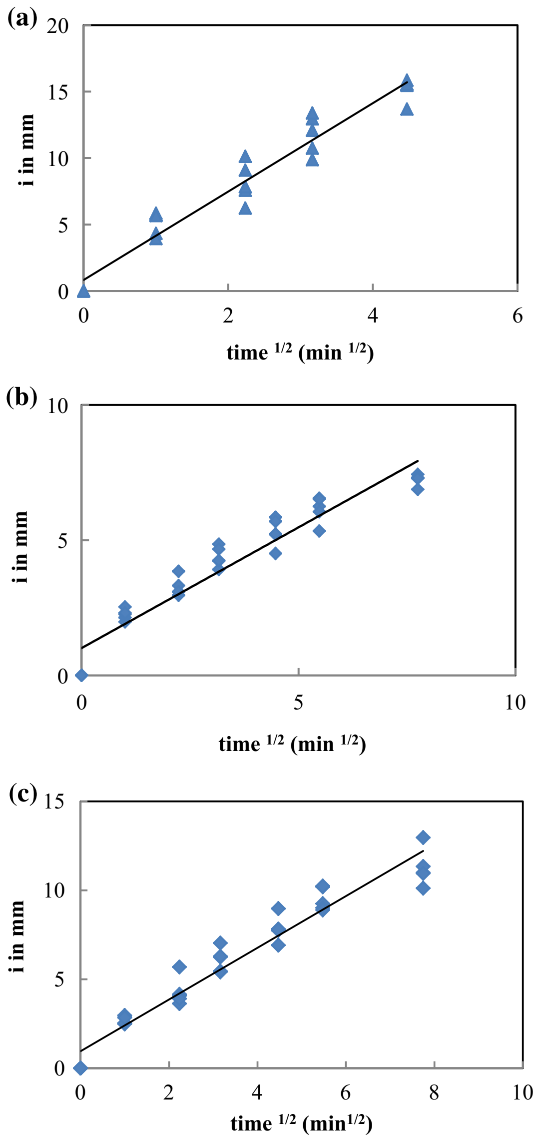

Fig. 8 **a** Absorption vs Time½ for Clay brick (Initial time) **b** Absorption vs Time½ for Industrial ash brick (Initial time) **c** Absorption vs Time½ for Fly ash brick (Initial time)

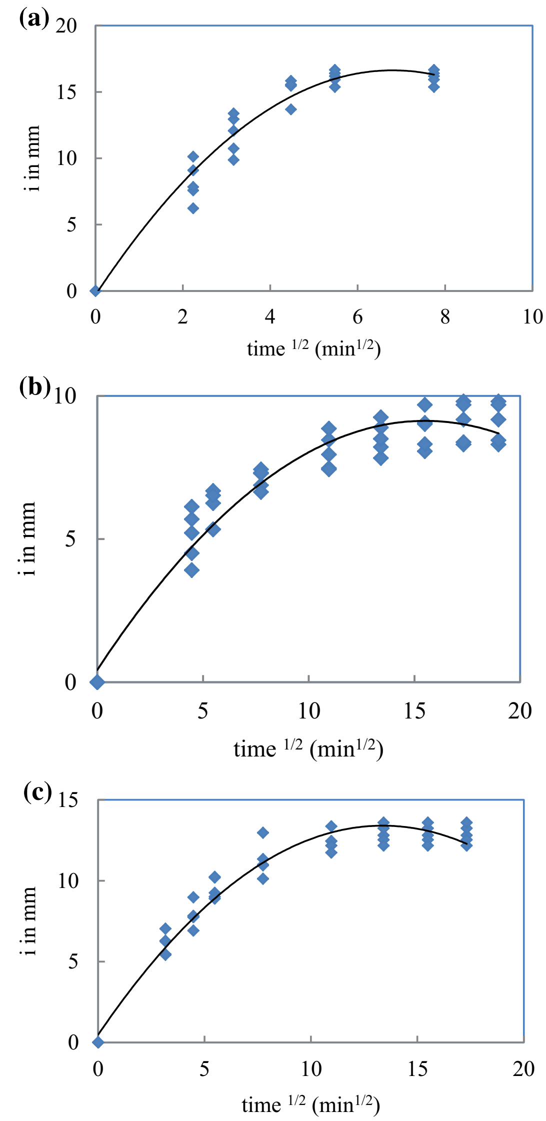

Fig. 9 **a** Depth of water absorption vs. Time½ for Clay brick **b** Depth of water absorption vs. Time½ for I-ash brick **c** Depth of water absorption vs. Time½ for Fly ash brick

Table 6 Saturated Sorptivity values of bricks

	Clay brick	Industrial ash brick	Fly ash brick
Sorptivity	3.326	0.893	1.452
t (min)	21	56	64

Table 7 Sorptivity values of bricks

	Clay brick	Industrial ash brick	Fly ash brick
Sorptivity	4.97	1.121	1.932
t (min)	60	360	290

The changes in the mass from initial to final stage of industrial ash specimen and fly ash specimen were observed using abrasion testing machine. From the test results, weight loss in % and thickness loss in mm were determined. The fly ash specimen and industrial ash specimens produced similar results. It is observed that the loss of thickness ranges from 3.75 to 4.67 mm for fly ash specimen and industrial ash specimen, respectively. The thickness loss for industrial ash specimen is 25% higher than that for fly ash specimen.

Table 8 Abrasion test results

Specimen type	Thickness in mm	Initial mass in grams	Thickness loss in mm	Weight loss in %
IAB	25	150	4.67	6.67
FAB	25	160	3.75	5.00

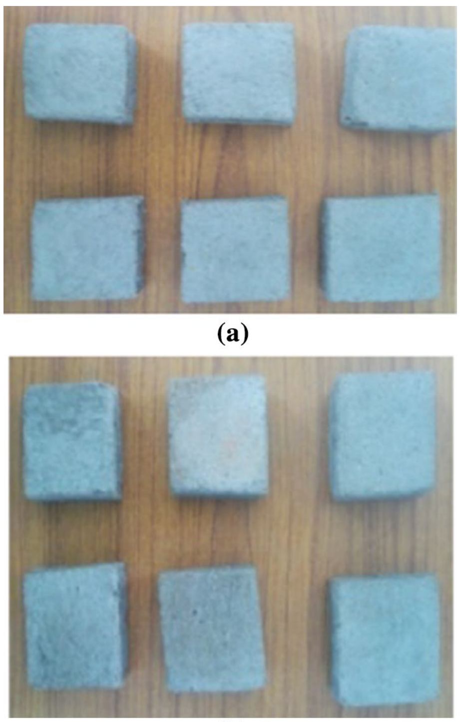

Fig. 10 **a** Specimens after abrasion test- Fly ash test specimen **b** Specimens after abrasion test- I-ash test specimen

5 Conclusions

Systematic experimental investigations were carried out. Detailed analysis of result has been made and the following conclusions have arrived.

All the mix classifications of industrial ash bricks satisfy the minimum compressive strength requirement of 3.5 N/mm^2 after 28 days of curing as per IS 12894:2002. The water absorption value for all mixes is less than standard allowable value of 20% as per IS 3475:1992 (Part 2). The weight density of industrial ash bricks ranges is indicating reduction in unit weight of clay masonry specified for clay brick. Te empirical relationship between the compressive strength with age of testing.

The exposure to sodium sulphate, sodium chloride and seawater results in a loss of strength of 14.2, 10.8 and 15.2% for industrial ash bricks as against 7.6, 6.5 and 8.2% in the case of conventional clay bricks, respectively. This performance is similar to that of fly ash brick. The sorptivity test conducted on coal ash brick, fly ash brick and clay brick indicates a dense microstructure in the case of I-ash bricks leading to a value of 4.97 for clay brick as against 1.21 for coal ash bricks.

References

Abbas S, Saleem MA, Kazmi SMS, Munir MJ (2017) "Production of sustainable clay bricks using waste fly ash: mechanical and durability properties. J Build Eng 14:7–14. https://doi.org/10.1016/j.jobe.2017.09.008

Akhtar JN, Alam J, Akhtar MN (2011) Bricks with total replacement of clay by fly ash mixed with different materials. Int J Eng Sci Technol 3(10):7338–7346. https://doi.org/10.25103/jestr.112

Bang RS, Ghugal YM, Pateriya IK (2012) Strength performance of pond ash concrete. Int J Earth Sci Eng 5(1):180–185. https://doi.org/10.21276/ijee

Bhangale PP, Nemade PM (2013) Study of pond ash (BTPS) use as a fine aggregate in cement concrete-case study. Int J Latest Trends Eng Technol 2(2):292–295. https://doi.org/10.1109/IECON.2012.6389024

Christy F, Tensing D (2011) Greener building material with fly ash. Asian J Civil Eng (Build Housing) 12(1):87–105. https://doi.org/10.17265/1934-7359/2019.08.001

Dayaratnam P (1987) "Brick and reinforced brick structures", Oxford and IBH, New Delhi, India.

Hakan C (2009) Toxic elements leachability tests on light weight fly ash bricks. Asian J Chem 21(4):2950–2956. https://doi.org/10.1155/2962

IS 1237: 1980, 'Specification for cement concrete flooring tiles', (First Revision), Bureau of Indian Standards, New Delhi

Rahman ME, Ong PJ, Nabinejad O, Islam S, Khandoker NAN, Pakrashi V, Shorowordi KM (2018) Utilization of blended waste materials in bricks. Technologies 6(1):1–12

Indian Standards (IS) (1992a) Indian standard methods of test of burn clay building bricks—Part 1: Determination of compressive strength, IS 3495, 3rd Rev., Bureau of Indian Standards, New Delhi, India.

Indian Standards (IS) (1992b) Indian standard methods of test of burn clay building bricks—Part 2: Determination of water absorption, IS 3495, 3rd Rev., Bureau of Indian Standards, New Delhi, India.

Indian Standards (IS) (1995) Indian standard code of practice for preparation and use of masonry mortars, IS2250, 5th Rev., Bureau of Indian Standards, New Delhi, India.

Vidhya K, Kandasamy S (2013) Study on properties of bricks manufactured using fly ash and pond ash. Int J Pollut Res 32(2):405–409. https://doi.org/10.1007/s11356-016-7021

Vidhya K, Kandasamy S (2016) Experimental investigations on the properties of coal-ash brick units as green building materials. Int J Coal Prep Util 36:318–325. https://doi.org/10.1080/02772248.2010.510922

Zhu L, Zhu Z (2020) Reuse of clay brick waste in mortar and concrete. Adv Mater Sci Eng 2020:1–11. https://doi.org/10.1155/2020/6326178