Study on preparation of brick blocks by using construction waste and sludge

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Abstract
The demand for scarce raw material has been increased with rise of construction. An ideal raw material is clay, which is abundantly used in manufacturing bricks. The proposed study aims at making a brick blocks with clay-free materials. Therefore, instead of clay, waste additives such as sludge waste, construction and demolition waste, and fly-ash are used as a binding material. These additives would contribute a better performance and properties without altering the desired strength. Sewage sludge is an important component of sewage disposal, but it is also ruinous to the environment. Construction and demolition (C&D) debris are a rising source of waste utilization. The objective of the proposed work is to eliminate the natural resources like clay and utilization of waste additives effectively in making brick blocks. The mix proportions are maintained at 30% sludge with 3:2:2, 2:3:2, and 2:2:3 (fly ash: cement: C&D), similarly, 40% sludge with 1:3:2, 2:3:1, and 3:2:1 and 50% sludge with 2:1:2, 2:2:1, and 1.5:1.5:2. The physicochemical properties include density, water absorption, pH, shrinkage, plasticity index, and efflorescence, and leaching characteristics were analyzed. Mechanical properties include compressive strength and thermal conductivity; mineralogical and microstructural analysis and durability aspects were carried out. The presence of organic matter influences the overall property. The stress distribution was induced by porosity and attained a maximum strength of 14.5 N/mm². Durability was influenced by compaction and temperature. At high temperature, the particles are well compacted. The concentrations of heavy metals are immobilized. Based on the above, it can be practically implemented in structures as well as in hidden masonry works.

Keywords Brick · Mix optimization · Construction and demolition waste · Sludge waste · Leaching · Firing temperature · Microstructure analysis

Introduction
Increasing sky-rise buildings with modern construction and urbanization enhance the demand for scarce raw materials for construction. An ideal example of scarce raw material is clay from quarries which has been used abundantly in the manufacturing of bricks. Urbanization is also facing a lot of problems in waste management from the domains of industrial and domestic. Consequently, a huge campaign is required to develop a solution by controlling waste management. On the other hand, it is necessary to safeguard the raw material which is undergoing the thermodynamic process for recycling. Based on the above concern, construction and demolition waste is the one where waste is utilized without any environmental effect (Goel and Kalamdhad 2017).

Disposal of sludge from the treatment plant is a tedious problem faced worldwide. The properties and characteristics of the sludge are primarily governed by the method of treatment as well as the quantity of material received from the source (Verlicchi and Masotti 2000). Typically, sludge consists of both organic and inorganic contents (Elliott et al. 1990; Ahmad et al. 2016). Generally, treated sludge is landfilled because of its non-hazardous and inert nature whereas developed countries are practiced in large numbers (Wang et al. 1992; Hidalgo et al. 2017). However, when the presence of geogenic contaminants such as iron, arsenic,
Researchers have also used various waste materials by blending in the manufacturing of bricks blocks. Agricultural waste (Madurwar et al. 2013; Kazmi et al. 2018a), marble sludge (Munir et al. 2021), glass waste (Silva et al. 2017; Kazmi et al. 2018b), bio-solids (Ukwatta et al. 2016) even sewage sludge (Liew et al. 2004; Wu et al. 2022) are also been used in the manufacturing of bricks. Sewage sludge contains a huge amount of moisture content that is not directly relevant to industrial use. Fibrous content is also present along with the sludge. Therefore, the presence of moisture can be controlled by composting, and thereby shredding of sludge becomes easier. Besides, the presence of fiber strengthens the product, which is highly important in load bearing structures as well as during the transportation. Generally, bricks are made using clay. The composition of clay includes alumina, ferric oxide, and silica which all has a similar composition of sludge from treatment plant (Hegazy et al. 2012). Therefore, sludge could be the substitute in manufacturing the clay bricks.

The purpose of the present study is to minimize the usage of natural resources (clay). Since, with rise in construction, obviously, the demand for raw materials also rises. With an ideal concept, sewage sludge, construction and demolition debris, and fly-ash have been replaced to the clayey material in making a brick sample. These materials are waste additives obtained from different sources. The contribution of waste additives in construction field as a building material would definitely impart better performance in structures. The presence of alumino-silicate would impart strength to the mix, load bearing will be contributed by the presence of fiber in the sludge, and formation of calcite would improve the abrasion. Performance of clay free brick depends on the concentration of additives, firing temperature, and methods involved in making a brick sample. The body of the research is to study the structural properties of the brick block using waste materials.

Research background

Goel and Kalamdhad (2017) used paper sludge compost in making brick blocks and reported that up to 10% of sludge provides a relevant strength as per the standards. Pokhara et al. (2019) used activated alumina sludge in making a brick block. The test reports inferred that 10% of sludge could successfully provide significant strength and recommended to use in low structural applications. Hassan et al. (2014) used arsenic iron sludge at different percentages such as 3%, 6%, 9%, and 12%. The strength depends on the percentage of sludge and the firing temperature. The optimum strength was achieved at 6% of sludge content. Liu et al. (2011) used dyestuff sludge from coagulation of wastewater at sludge to water ratio of 0.8:0.5. Hasan et al. (2022) used liming sludge at 2%, 4%, 6%, 8%, 10%, and 12% in making brick samples. Six percent of liming sludge satisfied the engineering properties. Simón et al. (2021) used dairy sludge and effluent sludge each with different percentages of 10%, 20%, 30%, and 35%. A total of 10% and 20% of sludge were found to be the acceptable strength property. Munir et al. (2018) used rice husk, marble, and glass sludge each with a constant percentage of 5%, 15%, and 25% in making brick products. The efflorescence rate for all types of sludge was found to be below 10%. Makni et al. (2021) used deinking paper waste sludge at 8%, 10%, and 12%. At 12% of sludge, improved strength with less density was achieved. Heniegal et al. (2020) used agriculture and water treatment sludge as a composite material in preparing brick blocks. Lower doses of sludge up to 5% improved the properties. Hosain et al. (2018) used textile mill sludge for manufacturing eco-friendly bricks at different percentages such as 10%, 25%, and 50%.

In previous literature works, the various waste additives were used in bricks which are all partially replaced to clay. With this literature gap, the present study aims at complete elimination of natural resources by providing a clay-free product. This would be achieved by using waste additives having similar properties of natural resources and such additives can be used as a binding material. The additives used in the present study would contribute a better performance and properties without altering the desired strength resulting in eco-friendly product.

Research significance

The proposed study aims at utilizing the waste materials generating day-to-day life in the field of Structural Engineering. An enormous amount of construction and demolition waste is generated during repair, rehabilitation, and during the demolition of the structures. Disposal of such waste is quite difficult and it requires a large land area. On the other hand, the generation of sewage waste is also rapid. Therefore, the objective of the proposed study is to:

1. Effective utilization of treated sludge waste from STP and waste additives in manufacturing brick samples.
2. Eliminating the natural resources such as clay.

The novelty of the proposed work is complete utilization of waste materials with clay-free products (no natural resources).
Materials and experimental methods

Materials

Class F fly ash is majorly rich in iron content. Fly ash is an ignition product of coal which is made of fine particles. These particles are driven out of boilers. The samples are obtained from Mettur power plant (11.7727° N, 77.8109° E). C&D wastes are obtained from PSG Institute, Coimbatore (11.0247° N, 77.0021° E). These C&D waste include clay, sand, gravel, silt, matrix, paints, etc. The chemical composition in each raw material would also play a major role in property aspects. Treated sludge waste was obtained from the sewage treatment plant at Prime aqua tech. The collected sludge was subjected to drying in an oven at a temperature of 105 °C for 2 days to remove the organic substance. The chemical composition of the materials is tabulated in Table 1.

Sample preparation

The size of the brick mold 225 × 110 × 75 mm as per ASTM specifications was fabricated. The properties of the materials are tested and the mixture is prepared through weight batching. Construction and demolition waste was crushed using a hammer and it is sieved through 1.75 mm. Treated sludge waste from the sewage treatment plant was subjected to drying in an oven at a temperature of 105 °C for 2 days. The additives include sludge, fly ash, cement, and C&D. The mix proportions are maintained at 30% sludge with 3:2:2, 2:3:2, and 2:2:3 (fly ash: cement: C&D), similarly, 40% sludge with 1:3:2, 2:3:1, and 3:2:1 and 50% sludge with 2:1:2, 2:2:1, and 1.5:1:5:2. The mix proportion of the additives is detailed in Table 2. Initially, the samples are subjected to sun-drying for 1 day and forwarded to heat curing for 4 h at a temperature of 1000 °C. The samples range from 2 to 3 kg. At different ratios, the weight may vary from 300 to 1100 g from the initial weight. The preparation of brick is illustrated in Fig. 1.

Research methodology

The foremost step in the research work is the collection of required materials from the source area. The collected samples were subjected to laboratory tests. The physicochemical properties of the materials are assessed. Finally, with the different ratios of the materials, the strength aspect is determined and it is compared with the control mix. Figure 2 details the flow process involved in the preparation of bricks.

Experimental methods

The physicochemical properties, mechanical properties, and durability aspects of the bricks are carried out as per the standards. The physicochemical properties include density, water absorption, pH, plasticity index, and efflorescence and leaching characteristics were carried out as per ASTM C67:2017. The shrinkage of the brick was tested as per the guidelines of ASTM C326:2018. Compressive strength was carried out as per ASTM C109/ C1099M-16a. According to ASTM standards, a 50 × 50 × 50 mm cube was cast and subjected to testing after heat curing at 1000 °C for 4 h. According to ASTM C518-17, thermal conductivity was taken at a sample size of 300 × 300 × 12 mm at a temperature of 400 °C, 600 °C, and 800 °C. Durability properties are followed as per ASTM C67-07 a, and the freeze-thaw test was carried out at 800 °C, 900 °C, and 1000 °C. The heating rate was maintained at 5 °C/min. Table 4 illustrates the properties of brick samples using treated sludge and waste additives.

Table 1 Chemical composition of additives

| Traces of element | Fly ash | Cement | Construction and demolition waste | Sludge |
|-------------------|---------|--------|-----------------------------------|--------|
| CaO               | 3.3     | 64.2   | 59.63                             | 19.23  |
| SiO2              | 55.2    | 22.01  | 17.23                             | 24.5   |
| Fe2O3             | 4.78    | 3.35   | 12.26                             | 6.29   |
| K2O               | 0.7     | 0.45   | 1.72                              | 1.8    |
| TiO2              | 1.7     | 0.16   | 1.36                              | 0.17   |
| Al2O3             | 26.7    | 5.25   | 1.98                              | 11.56  |
| MgO               | 2.6     | 1.42   | 0.25                              | 1.37   |
| MnO               | -       | -      | -                                 | 0.64   |
| SO3               | 1.8     | 2.17   | 2.52                              | 4.91   |
| CuO               | -       | -      | 0.055                             | -      |
| Na2O              | 0.36    | 0.31   | -                                 | 0.31   |

Table 2 Mix proportion of additives

| Mix   | Sludge | Fly ash | Cement | C&D |
|-------|--------|---------|--------|-----|
| S30-01| 30     | 30      | 20     | 20  |
| S30-02| 30     | 20      | 30     | 20  |
| S30-03| 30     | 20      | 20     | 30  |
| S40-01| 40     | 10      | 30     | 20  |
| S40-02| 40     | 20      | 30     | 10  |
| S40-03| 40     | 20      | 30     | 10  |
| S50-01| 50     | 20      | 10     | 20  |
| S50-02| 50     | 20      | 10     | 20  |
| S50-03| 50     | 15      | 15     | 20  |
Results and discussion

Bulk density

Burning temperature, presence of raw materials, and method of manufacturing are the main factors on which bulk density of the brick depends (Okunade 2008b). Phonphuak et al. (2016) reported that the bulk density of normal brick ranges between 1.8 and 2.5 g/cm³. The bulk density of S30-01, S30-02, S30-03, S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03 decreased from 2.72 to 1.8 g/cm³. Figure 3 infers that the bulk density of clay-free brick gradually diminishes as the percentage of sludge increases. A possible reason for the significant reduction is due to the presence of a higher amount of organic matter and hydrate of sludge leading to reduce density. Similar results were found in the case of using tannery sludge (Liew et al. 2004). Also, the synthesis of bricks at a higher temperature may result in calcite decomposition and release of CO₂ by leaving the pores in the bricks (Cultrone et al. 2001, 2004). The significant reduction of bulk density is also related to shrinkage. Increasing the percentage of sludge decrease the weight, increase the shrinkage, and conversely decrease the bulk density because of evaporation of moisture and organic matter.

Water absorption

A major determinant of a block’s durability is water absorption. From the test results (Fig. 4), it infers that for S30-01, S30-02, S30-03, S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03, the water absorption increases by 4%, 2.6%, 6.6%, 7.3%, 8%, 10.6%, 9.8%, 13.3%, and 9.3% respectively from the control mix S0. As per the standards of ASTM C62:2017, for moderate weathering resistance, water absorption should be less than 22%. Furthermore, Phonphuak (2013) and Hossain et al. (2018) reported that a maximum of 20 to 30% of water absorption can be accepted. Thereby, the water absorption of the brick sample is within the limit.

pH

pH influences the mechanical and durability properties of the product. The main purpose of carrying out a pH test in bricks is to determine the concentration. When concentration decreases below 6, the sample becomes acidic and it is most harmful resulting in deterioration. The samples are immersed in water at a pH of 7.8. The pH of treated sludge and C&D estimates to be 6.25 and 8 respectively. On a combination of additives, up to 30% of sludge, pH maintains a
value of 7–8. Beyond 30% of sludge, pH fluctuates randomly as shown in Fig. 5. The reason behind fluctuation is the reaction of metallic and non-metallic compounds present in the additives.

**Shrinkage**

Volume shrinkage of the brick sample is shown in Fig. 6. Phonphuak (2013) reported that when the water
evaporates, the brick samples shrink under sintering. The shrinkage of conventional brick sample was found to be 7%, whereas in addition of additives, the shrinkage of S30-01, S30-02, S30-03, S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03 decreases by 3%, 3%, 4%, 6%, 6%, 7%, 7%, 7.5%, and 7% respectively. Görhan and Şimşek (2013) and Phonphuak (2013) reported that by increasing the waste additives, the shrinkage of the brick decreases. As reported by Okunade, 2008a, the shrinkage limit should not exceed 8%. In this proposed work, the shrinkage of all sludge-treated brick samples is within the specified standard limit. Generally, shrinkage undergoes cracking by affecting the performance of the product (Mekki et al. 2008). The waste additives considered in this study lower the shrinkage property and these materials can be considered for manufacturing a low shrinkage material.

Plasticity index

The plasticity index of the conventional brick was found to be 17%. The plasticity index for S30-01, S30-02, S30-03, S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03 was found to be 18.5%, 14.5%, 7.5%, 7.2%, 6%, 6.1%, 6.2%, and 5.5%. Figure 7 demonstrates that an increase in the percentage of sludge decreases the plasticity index. The presence of organic matter increases the flowability. As reported by the National Institute of Interdisciplinary Science and Technology, a plasticity index greater than 23 is better for making

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**Fig. 3** Bulk density

![Graph showing bulk density](image)

**Fig. 4** Water absorption

![Graph showing water absorption](image)
normal bricks. For hand molding, the plasticity index of less than 18 is also recommended, although it depends on size and strength.

**Efflorescence**

The efflorescence of conventional brick was found to be 5%. At 30% of sludge, the efflorescence decreases by 20% for S30-01, S30-02, and S30-03 from the control mix S0. At 40% and 50% of sludge, the efflorescence increases by 22%, 30%, 34%, 38%, 44%, and 50% for S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03 respectively as shown in Fig. 8. The presence of ferric and calcium oxides in the additives occupies a major role in efflorescence (Velasco et al. 2014). A decrease in efflorescence at 30% of sludge is due to the reduced amount of ferric and calcium oxides compared to clayey material. However, at 40% and 50% of sludge, a higher amount of oxides were found compared to the clayey material. When the porosity increases, it facilitates the salt deposition on the brick samples (Kazmi et al. 2016, 2017). As per the standards, 10% of efflorescence was found to be slight. Hence, in this proposed study, all the samples incorporating sludge and waste materials show efflorescence less than the specified value (10% — slight).

**Presence of heavy metals**

The heavy metals are detected both in conventional and sludge-based brick samples. An atomic absorption spectrometer was used to carry out the leaching characteristics. The
concentration of the sludge-based bricks is compared with the conventional as tabulated in Table 3. As seen clearly, sludge-based bricks exceed the concentration compared to conventional bricks. Moreover, these concentrations may solidify as metal oxides in the sample (Liew et al. 2004). With an increase in temperature, the concentration decreases since the formation of the amorphous phase take place with SiO₂ (Verbinnen et al. 2014). The concentration of heavy metals does not affect since it is immobilized and disposed of safely among calcination of bricks.

**Compressive strength**

Compressive strength was performed conforming to the standard as shown in Fig. 9. The test results infer that only at 30% of sludge, the strength increases from the control mix. For S30-01 and S30-02, the strength increases by 1.43% and 4.3% respectively from the control mix S0. For S30-03, the strength becomes neutral to the control mix. For S40-01, S40-02, S40-03, S50-01, S50-02, and S50-03, the strength decreases by 0.7%, 0.71%, 10%, 15.8%, 2.15%, and 16.5% respectively from the control mix. The density and porosity play a major role in determining the

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**Table 3** Detection of heavy metals

| Materials | Zn | Cu | Fe | Pb |
|-----------|----|----|----|----|
| Clay      | 1.2| 0.11| 33.5| 0.7 |
| Sludge    | 2.29| 2.36| 22.6| 2.72 |

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Fig. 7 Plasticity

![Plasticity Graph](image1)

Fig. 8 Efflorescence

![Efflorescence Graph](image2)
A decrease in strength is due to the low density and high porosity. Stress distribution will be induced by high porosity and it also reduces the strength and structural compactness of the brick (Munir et al. 2018). A decrease in compressive strength is also contributed by non-homogeneous material obtained by blending the waste material (Hwang and Huynh 2015). The strength of the brick depends on the standards of the building. National Engineering service of Pakistan 2007, Standards Australia, masonry units 2005, Ministry of Public works and Housing 1997, and Bureau of Indian standards 1992 reported that minimum compressive strength required for the building is 5–8 Mpa. In this study, the brick samples satisfied the minimum requirement.

The correlation between the density, water absorption, and compressive strength of the sample would be referred to from the test results (Table 4). From the test results, it infers that there is no correlation between density and compressive strength. Since the inclusion of sludge in the matrix gradually decreases the density whereas the compressive strength fluctuates depending on the concentration of the additives. Similarly, Mubiayi et al. (2018) reported the same behavior of no correlation between density and compressive strength while incorporating clay, fly ash, and jarosite. Similar reports were presented by Maza-Ignacio et al. (2020), Eliche-Quesada et al. (2018), dos Reis et al. (2020), and Sarani et al. (2018). This behavior would be due to the microstructural changes in the matrix (Sarani et al. 2018). On the other hand, there is a positive correlation between water absorption and compressive strength. As inferred from the results, the minimum water absorption and maximum compressive strength were attained for a mix S30-20.

**Thermal conductivity**

The degree of compaction determines the insulation property. The thermal conductivity of samples was carried out at 400 °C, 600 °C, and 800 °C as shown in Fig. 10a–c. At the temperature of 400 °C, the consolidation of the particles has not started whereas the organic matter evaporated due to the porous structure. On the other hand, the thermal conductivity in the pores is lower than in solid particles and the point of contact is direct. These factors reduce the transfer of heat resulting in lower conductivity of heat. At 600 °C and 800 °C, the thermal conductivity of the brick sample is increased even though there is a reduction in the mass of the sample as noted at 400 °C by evaporating the organic matter. An increase in thermal conductivity is because the particles are highly consolidated. Hwang and Huynh (2015) reported that the compactness of the sample improves the heat transfer. Also, temperature plays a major role in modifying the insulation property and provides a better application in energy-saving structures.

**Mineralogical and microstructural analysis**

A mineral compound present in the clay is expected to be the quartz on a major scale (Pokhara et al. 2019). From Fig. 11, the predominant phase mineral present in the clay-free brick is quartz and calcite which is identified through X-diffraction analysis. The incorporation of 30% sludge into the mix does not alter the mineral composition compared with the mix S0. However, a minor phase of calcite was observed indicating the possibility of thermal degradation. As discussed earlier by Cultrone et al. (2001), the successive fusion takes place during heat curing when degradation occurs from calcite to calcium oxide. From the diffraction pattern, the presence of

| Mix  | Bulk Density (g/cm³) | Water absorption (%) | pH | Shrinkage (%) | Plasticity (%) | Efflorescence (%) | Compressive strength (N/mm²) | Thermal conductivity (W/m * k) | Freeze thaw (strength loss %) |
|------|----------------------|----------------------|----|---------------|---------------|-----------------|-----------------------------|-------------------------------|-----------------------------|
| S0   | 2.8                  | 15                   | 7.6 | 7             | 8.5           | 5               | 13.9                        | 0.24 0.33 0.45               | 13.6 21.8 48.1               |
| S30-01 | 2.72               | 21                   | 7.9 | 3             | 17            | 4               | 14.1                        | 0.29 0.35 0.46               | 11 19.1 45.6                |
| S30-02 | 2.68               | 19                   | 7.8 | 3             | 18.5          | 4               | 14.5                        | 0.25 0.31 0.47               | 12 20 47                    |
| S30-03 | 2.54               | 25                   | 7.12| 4             | 14.5          | 4               | 13.9                        | 0.3 0.33 0.47               | 12.5 21.2 48.2              |
| S40-01 | 2.32               | 26                   | 12.23| 6             | 7.5           | 6.1              | 13.8                        | 0.31 0.4 0.53               | 13.9 23.5 52.1              |
| S40-02 | 2.27               | 27                   | 15.42| 6             | 7.2           | 6.5              | 14                          | 0.29 0.39 0.52               | 14.5 25 56.5                |
| S40-03 | 2.18               | 31                   | 13.9 | 7             | 6             | 6.7              | 12.5                        | 0.35 0.42 0.55               | 17.5 27 57                  |
| S50-01 | 1.92               | 30                   | 10.12| 7             | 6.1           | 6.9              | 11.7                        | 0.39 0.48 0.6               | 18.6 28.2 59.2              |
| S50-02 | 1.85               | 35                   | 7.74 | 7.5           | 6.2           | 7.2              | 13.6                        | 0.39 0.49 0.61               | 18.8 29.1 60.5              |
| S50-03 | 1.8                | 29                   | 8.12 | 7             | 5.5           | 7.5              | 11.6                        | 0.41 0.5 0.61               | 19.2 30.9 62                 |
Table 5  Comparison of present findings with the previous findings

| Additives                        | Mix proportion (%) | Exposure condition | Properties                                      | Reference                  |
|----------------------------------|--------------------|--------------------|-------------------------------------------------|----------------------------|
| Paper mill sludge                | 0, 5, 10, 15, 20   | Firing temperature — 850 and 900 °C Heating rate — 2 °C/min | Optimum percentage (OP) — 10%, compressive strength (CS) — 9.97 MPa, water absorption (WA) — 18.65%, shrinkage — 4.65 | Goel et al. 2021 |
| Activated alumina sludge         | 0, 5, 10           | Firing temperature — 900 °C | OP — 10%, bulk density (BD) — 1.69 g/cm³, WA — 23%, CS — 5.4 MPa, thermal conductivity (TC) — 0.19 Wm⁻¹k⁻¹ | Pokhara et al. 2019 |
| Arsenic iron sludge              | 0, 3, 6, 9, 12     | Firing temperature — 500 and 1000 °C at 12 h | OP — 6%, CS — 15.1 MPa | Hassan et al. 2014 |
| Dye stuff sludge                 | Cement: sludge 1:0.5, 1:0.8, 1:1 | Firing temperature — 30 to 900 °C Heating rate — 10 °C/min | CS — 41.3 MPa | Liu et al. 2011 |
| Liming sludge                    | 2, 4, 6, 8, 10, 12 | Firing temperature — 1000 °C | OP — 6%, CS — 27.50 MPa, BD — 2.18 g/cm³, WA — 10.46%, shrinkage — 5.03% | Hasan et al. 2022 |
| Dairy and effluent sludge        | 10, 20, 30, 35     | Firing temperature — 950 °C Heating rate — 1 °C/min | OP — 10%, CS — 17 MPa, BD — 1.725 g/cm³ | Simón et al. 2021 |
| Rice husk                        | 25                 | Firing temperature — 25 to 1100 °C | CS — 13 MPa, WA — 21%, TC — 0.6 Wm⁻¹k⁻¹, efflorescence — 8% | Munir et al. 2021 |
| Marble                           | 5                  | Heating rate — 10 °C/min | | |
| Glass sludge                     | 5                  | Heating rate — 10 °C/min | OP — 12%, CS — 4.65 MPa, WA — 16.58% | Makni et al. 2021 |
| Deinking paper sludge            | 8, 10, 12          | Firing temperature — 20 to 850 °C | OP — 15(PM), 30(CS); CS — 36.6 MPa, WA — 37.4%, BD — 1.37 g/cm³, TC — 0.742 to 0.155 Wm⁻¹k⁻¹ | Yaras 2020 |
| Paper mill Carbonation sludge    | 5, 10, 15          | Firing temperature — 1000 and 1100 °C Heating rate — 5 °C/min | OP — 30%, CS — 13.9 MPa, WA — 25%, BD — 2.68 g/cm³ | Present study |
| Textile sludge                   | 10, 25, 50         | Firing temperature — 450 °C for 24 hours | BD — 1.8 g/cm³ | Hossain et al. 2018 |
| Sludge waste and C&D debris      | 30, 40, 50         | Firing temperature — 400 to 1000 °C Heating rate — 5 °C/min | OP — 30%, CS — 13.9 MPa, WA — 25%, BD — 2.68 g/cm³ | Present study |

Fig. 9  Compressive strength
Fig. 10  a Thermal conductivity at 400 °C. b Thermal conductivity at 600 °C. c Thermal conductivity at 800 °C.
fusion can be noted; however, in the proposed sludge, the minor phase impurities are not present.

The FE-SEM of sintered products provides a great impact on mechanical properties. The clay-free brick at S30-02 (Fig. 12a) seems to be more porous. The porous structure is due to the presence of organic matter and moisture content (Juel et al. 2017). When the bricks are subjected to heating, the presence of organic matter and moisture content is evaporated thereby leaving behind pores. Moreover, CaCO₃ and CaO facilitate the porous structure. When these chemicals are decomposed, a gaseous CO₂ is released and pores are left behind (Ukwatta et al. 2016). At S30-02, the particles are cohesively packed and homogenous. However, the presence of fiber (Fig. 12b and c) would improve the yielding behavior. Figure 12d shows that the particles are hollow spheres, which imparts the mechanical property. At increasing temperature, the formation of pores is subjected to densification and vitrification phenomena. The surfaces are unevenly weathered at higher temperatures as shown in Fig. 12e.

**Durability**

Durability is the capability of the specimen to withstand the aggressive environment and it is influenced by the porous nature, which is related to firing temperature (Hegazy et al. 2012). According to ASTM C67-07a, the temperature of 800 °C (Fig. 13a), 900 °C (Fig. 13b), and 1000 °C (Fig. 13c) is maintained to meet the standards. When the temperature falls below 800 °C, it becomes difficult to test since the brick breaks after freezing and thawing. Only at a temperature of 800 °C, the calcination becomes adequate. It is also evident that strength loss with increasing temperature is related to compactness. At low temperatures, the bricks are porous so that water frozen is expanded through the incompact particles (Scherer 2004). Contradictorily, at high temperatures, mitigation of frozen water cannot take place.

**Comparison of previous findings with present study**

As reported by Murmu and Patel (2018) and Al-Fakih et al. (2019), manufacturing of bricks depends on properties of raw materials, method of preparation, and curing and characteristics analysis. These factors provide a variation in physicochemical properties, mechanical properties, thermal properties, and durability aspects. Table 5 summarizes the various additives used in manufacturing bricks and that of compared with the present study.
Conclusion

With the aim of the present study, the waste additives were replaced with natural resources (clay) to make a clay-free brick block. To make a statement valid, the brick samples incorporating waste additives at different proportions have been tested against various properties including physicochemical, mechanical, durability, and microstructural analyses. The performance and properties were compared...
Fig. 13  a Durability — strength loss at 800 °C. b Durability — strength loss at 900 °C. c Durability — strength loss at 1000 °C.
to the conventional sample. Based on the experimental results, the following conclusions were achieved:

1. Water absorption, pH, and plasticity index of the sludge treated bricks were found to be 19%, 7.8, and 18.5% respectively at 30% pH sludge. An increase in sludge content decreases the plasticity index since the presence of organic matter influences the flowability.

2. The heavy metals are found to be more excess in sludge treated brick than in conventional. However, the concentration does not influence since the heavy metals are immobilized and disposed of safely among calcination of bricks.

3. The compressive strength of the brick depends on density and porosity. The maximum compressive strength of 14.5 Mpa was achieved at 30% of sludge. Stress distribution was induced by high porosity.

4. The thermal conductivity of the sample is influenced by the compaction and temperature. An increase in thermal insulation is due to the high compaction of the particles.

5. Microstructural analysis revealed that the presence of fiber in the matrix would improve the yielding behavior.

6. Durability is also influenced by compaction and temperature. At low temperature, water frozen is expanded through incompact particles whereas, at high temperature, the particles are well compacted. At high temperatures, expansion of frozen water does not take place.

7. Natural resources are being affected in huge amounts. Therefore, with the objective of clay-free material, the waste additives are induced in the preparation of brick blocks. The waste additives provide a significant strength within the standard limits. Therefore, it is suggested that these bricks can be practically implemented in structures as well as in hidden masonry works.

The limitation of the proposed study would be the utilization of sludge waste of up to 30%. Beyond 30%, the presence of toxic elements in the sludge will leach out and contaminates the soil and groundwater. The concentration of toxic elements can be immobilized under the calcination of samples at 800 °C.

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Author contribution RV contributed to formal analysis and data curation. DS provided conceptualization, methodology, and writing — original draft. AKK contributed to formal analysis and supervision.

Data availability Data will be made available on request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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