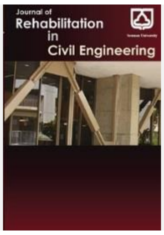

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Utilization of Construction and Demolition Waste for Sustainable Masonry: Experimental Analysis and Microstructural Insights

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ABSTRACT

Construction is an ever-growing industry that significantly contributes to the global economy and provides infrastructure for many diversified sectors such as housing, transportation, water supply, irrigation, and many other projects. The construction of these projects leads to increased demand for conventional materials in the form of bricks, cement, steel, aggregates, and so on, which has adversely impacted the environment. It has become inevitable for construction professionals to look for energy-efficient sustainable alternatives for conventional building materials. In the present experimental work, the authors have used construction waste as a sustainable alternative by replacing conventional materials partially or completely in masonry units. Construction wastes collected from nearby dump yards are segregated and processed to get the recycled aggregates which are later tested for quality. These aggregates and binders are proportioned to cast stabilized blocks having different engineering properties. These blocks when tested in compression at 7, 14 and 28 days, have resulted in strengths in the range of 2.82 MPa to 6.82 MPa. The blocks exhibiting higher strengths were further tested for physical, mechanical, and durability properties namely dimension, density, water absorption, scratch, and efflorescence. In addition, these blocks and the basic materials are tested for their microanalysis through SEM, XRD, and FTIR. Finally, prisms are cast and tested as a masonry unit at 7, 14, and 28 days. These blocks showed a maximum dry compressive strength of 4.1 MPa. From the study, it is observed that the stabilized recycled aggregate with 10% cement binder has resulted in acceptable alternative blocks having good engineering properties. The same is presented in the graphical abstract as well.

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1. Introduction

The supply and demand for affordable housing are vastly out of balance due to urbanization. This gap between supply and demand is intensified by expensive construction materials such as cement, brick, steel, etc. These construction materials account for approximately 60% of a construction project's total cost [1]. As the construction business booms, so does the demand for natural conventional building materials. One such demand is the demand for river sand, as it is used as a primary material in the manufacturing of many construction materials, which has led to its illegal mining, causing both social and environmental problems. Further causing a reduction of natural sand resources, ruin of riverbeds, and a decline in river water quality and riverbank growth.

On the other hand, the production of construction materials has many issues as discussed below. It is now widely recognized that global warming is a serious environmental problem and that the community bears great responsibility for it. GHG[1]s, water vapour, halogenated hydroxides, ozone, nitrous oxides, methane, and carbon dioxide, all share the credit for the increase in global warming. Studies have shown that carbon dioxide (CO_2) is one of the primary causes of global warming and contributes to 9-26% of the GHG effect. Although there are several factors resulting in CO_2 emission, undeniably, the different lifecycle phases of a building (identified as component manufacturing, material handling, assembly, construction, operation, service, and end-of-life) result in energy use and carbon release [2]. One such instance is the making of fired bricks, which is one of the causes of increasing GHG emissions into the atmosphere. At the same time, this type of brick is also assessed as consuming a lot of energy and is not environmentally compliant [3]. Concurrently about 9% of the total construction materials end up as waste. India alone produces 150MT of Construction Demolition Waste from here on abbreviated as [2]CDW which accounts for 35-45 % of global CDW and recycles only 1% [4].

A primary step to reduce the aforementioned harm is to look for building materials that are sustainable for both the existing and future generations, as the construction industry consumes raw materials at a rate that is second only to the food industry [5]. Therefore, the traditional method of using unburnt brick in the form of earth construction could be considered. The practice of using mud as a construction material in several forms dates back to the beginning of mortal civilization where we learned to make structures. The ruins of Mesopotamian communities, which date to roughly 4000 BC, and those found in the Indus valley, which dates back between 3300 and 1900 BC, can be used to demonstrate some of these. Soil has always been the main structural material for conventional embankment systems. Recently, important discoveries have been accepted to develop earth-based technologies like Compressible Stabilized Earth Blocks (CSEB) and rammed earth to make the earth a sustainable structural material. Stabilized Earth Blocks from here on abbreviated as SEB[3] have been used for the past 60 years as a reliable wall block in place of fired bricks and blocks. However, due to the significant issues affecting the quality and stability of these blocks, concrete blocks are more dynamic but are not socially respected due to their environmental impact [6]. The use of top fertile red soil in the making of burnt clay bricks and SEBs will lead to the loss of the top layer of soil which is more suitable for agriculture and destroys the natural habitat as reported by [7]. Consequently, it is important to look for sustainable alternative building materials that cost less and are more energy efficient, with similar properties to conventional materials used in the construction industry.

Contemporary works concentrate on achieving a circular economy, and to that end use industrial waste in the form of geopolymers as binders in the manufacturing of geopolymer concrete [8], CDW is also used

[1]GHG- Green House Gas
[2] CDW- Construction Demolition Waste
[3] SEB- Stabilized Earth Block

in the production of recycled aggregate concrete [9], Agricultural waste is also used as the fibers in the manufacturing of agro-waste-based concrete [10]. Although they've successfully looked for substitutes, the present work suggests an energy-efficient alternate solution of utilizing industrial waste in the manufacturing of masonry units using locally available CDW. Since geopolymers will be an unreliable option as they are not available in the nearby regions, the current work aims to study the feasibility of using recycled aggregate to produce unburnt masonry units. The novelty of the present work is the use of two types of CDW: cement-based CDW and brick-based CDW. These CDW are used in combination with two types of binders, that is cement and lime.

This article is divided as follows; Section 1 involves the introduction to present work. Section 2 provides an outline of the work carried out in the production of masonry units and their pros and cons. Section 3 concentrates on the methodology employed in stabilizing industrial waste materials by contemporary researchers and the experimental program followed in the present work. Section 4 gives the manufacturing procedure used in the production of stabilized blocks. Section 5 gives the experimentation and validation of materials formed by recycling C&D[4] waste. Section 6 explains the morphology of the materials used in the production of stabilized blocks. Section 7 describes the durability test carried out on the manufactured stabilized blocks. Section 8 discusses the prism test on masonry made of stabilized recycled blocks. In section 9 cost analysis for the casting of recycled aggregates stabilized blocks in the laboratory is discussed. The present work is concluded in section 10.

2. An outline of a sustainable solution by recycling the CDW as FA in stabilized blocks

Unburnt and fired bricks both have a place in construction, brick is now recognized as one of the basic building materials. Even while burnt bricks outperform unburnt masonry units, they need energy. Particularly developing nations like India, heavily rely on baked bricks to construct inexpensive houses, which results in unsustainable development. Earthen architecture is no longer as common as it once was due to improvements in contemporary building materials like concrete and steel. Still, it is believed that more than two billion people worldwide today reside in mud huts. With a heightened awareness of environmental damage and energy use brought on by industrialized materials, mud construction is gaining popularity as a sturdy building material [11]. Researchers have become interested in earthen soil as a building material because of its accessibility and minimal influence on the environment. However, on the other hand in emerging countries, waste disposal from the industrial and agricultural regions is a major problem. Researchers added these surplus additives to the Earth's matrix to improve its functionality [12]. Jannat et al., 2020 [12] steered a thorough investigation into the use of substitute constituents to replace traditional ones used in the mass production of building materials and components into two main categories, such as agricultural waste and non-agricultural waste. Non-agricultural waste is primarily made up of industrial residues, and industrial waste and is used in the manufacturing process by completely or partially replacing conventional materials, and thus innovative blocks are validated by testing them for their specific properties. According to Contreras et al., 2016 [13] 50% of all municipal solid waste is CDW, frequently dumped in the wrong places. There is still a lack of knowledge about how to recycle waste from CDW, especially into useful products like building materials [14]. As an alternative for soil-sand mixtures and sand, several studies looked at the technical properties of CSEB[5] integrating waste crushed bricks [11]. Contreras et al., 2016 [13] in their work, recycle C&D[6] waste to make bricks

[4] C&D- Construction and Demolition
[5] CSEB- Compressed Stabilized Earth Blocks
[6] C&D- Construction and Demolition

instead of using natural aggregates. A single-shaft hydraulic press is used to compress. Lime and cement are used as binders. Construction waste (primarily crushed concrete) and river sand are used to control both the finer content and the larger particles, and the chosen soil is upgraded to 5%, 10%, 15%, and 20% finer grade [15]. To optimize the compaction of the grain according to the grain compaction theory, the soil is modified by g river sand and construction waste, and stabilizer cement is used at 6%, 8%, and 10%. Joshi et al., 2019 [16] used CDW by crushing and segregating the waste and using it in the preparation of SEB and also presented an empirical investigation of product-based research. Kongkajun et al., 2020 [17] produced earthen cement bricks from locally discarded Clay Bricks Waste (CBW) and Soft Slurry (SS) from the fiber cement industry using industrial waste in their place to conserve raw materials.

Further, a thorough literature survey on employing CDW in the production of stabilized blocks gives us the following information. Malkanthi et al., 2020 [18] reported that the maximum Compressive Strength (CS) of 5.5 MPa was achieved with 5% cement and 5% lime used as binders and 10% fines of soil. Kasinikota et al., 2021 [11] reported that 24% of recycled brick powder and 76% of soil sand at 28 days gave a CS[7] of 9.57 MPa and increased water absorption with an increase in brick waste. Kongkajun et al., 2020 [17] noticed maximum CS at 10% replacement of soil by CDW. Nagaraj and Shreyasvi, 2017 [19] reported that the mixture of 8% cement, 2% lime, 30% municipal solid waste, and 60% quarry dust has the best CS and water absorption. Venkatarama Reddy et al., 2007 [20] found that optimum clay content leads to maximum strength in the range of 14-16%, and water absorption decreases with an increase in clay content. Venkatarama Reddy et al., 2007 [20] reported that when the blocks were subjected to scratch test the blocks with 16% clay content and 8% cement content showed less weight loss. Sarangapani et al., 2005 [21] reported that the prism CS of 5.24 MPa is achieved with cement mortar (1:4) proportion showing type III type of failure that is a combination of brick and bond failure. Kamplimath and Joshi, 2015 [22] noticed among the various alternatives considered for the fine aggregate in the manufacturing of cement mortar (1:6) of cement and quarry dust gave a CS of 14.56 MPa at 28 days. Malkanthi et al., 2021 [15] obtained a maximum CS of 8.7 MPa with 10% fines and 10% cement by addition and gradation of CDW, soil, and sand with cement. The significant fact is that there is not much research reported on the manufacturing of stabilized blocks in combination with cement-based CDW and recycled brick powder as fine aggregate.

The present work concentrates on the study of the behaviour of cement-based CDW from masonry and recycled brick waste from masonry as fine aggregate in the production of stabilized blocks with varying proportions of cement, lime, and CDW. Since the demolition of a masonry wall results in debris which is majorly composed of burnt clay bricks, mortar, and lime, this debris does not find its application in any of the activities in the construction sector and goes down as a landfill. Using these materials in landfills has proved to be hazardous, as these debris are non-biodegradable, and result in the formation of unstable ground for any construction activities. In the present work, the masonry waste from nearby landfills is collected and processed as shown in Figure 4 (a) (b) (c). The processed fine aggregates are segregated into separate cement-based fine aggregates and are considered (CDW-1) and burnt clay brick powder is considered (CWD-2).

3. Methodology

Figure 1 shows the flow chart demonstrating the methodology adapted for block manufacturing research. It integrates experimental and analytical stages to evaluate the feasibility of using recycled aggregate in stabilized masonry units.

[7] CS- Compressive Strength

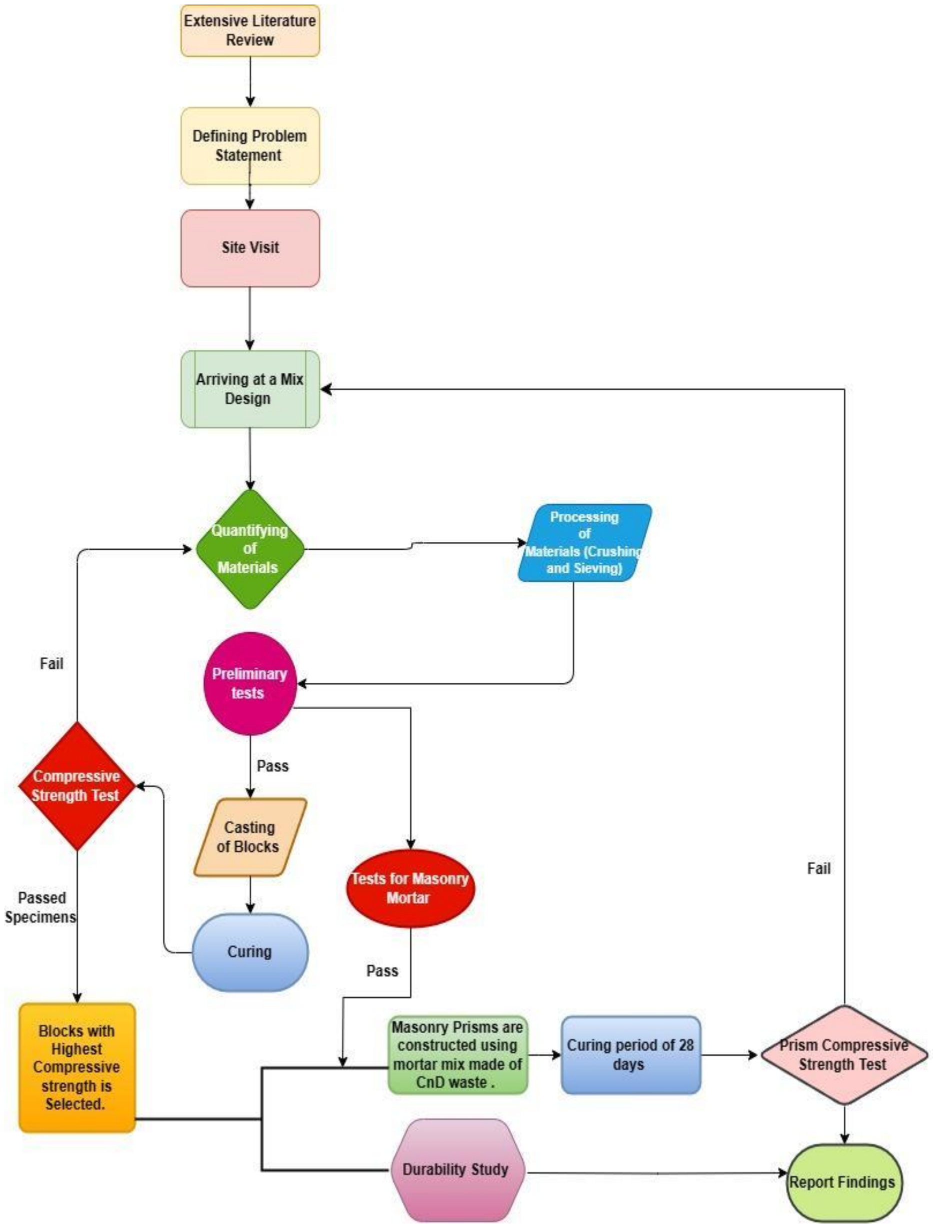


Fig. 1. Flowchart showing methodology adapted in the block manufacturing process.

Figure 1 shows that the process begins with an extensive literature review to understand contemporary research and define the problem statement. Material assessment and sampling is carried out by a site visit. A mix design is developed based on the findings that are best suited to the research requirement. Materials are processed and quantified through crushing and sieving. Material properties are evaluated by conducting the preliminary tests, if the materials pass these tests the blocks are cast. Masonry mortar tests are conducted separately to ensure compatibility with the masonry units. Post-completion of the curing phase the blocks are subjected to a CS. The specimen with the highest CS is selected for further analysis. Masonry prisms are constructed using the selected block with mortar from recycled aggregate. The prisms are examined for CS after 28 days of curing to evaluate the structural integrity and durability. The findings are reported, concluding the research process with valuable insights into the potential of RA in sustainable block manufacturing.

4. Manufacturing of blocks

The nearby landfills which majorly consist of masonry waste were located and collected. The masonry waste is grounded by using the road roller available at the site. The ground powder is segregated into two types of CDW, in which CDW-1 is composed of cement-based waste, and CDW-2 is composed of brick powder. The mix proportion is so considered to verify the applicability of construction waste as a replacement for conventional soil. One variety of the CDW is varied along with conventional soil keeping the other mix constant. Six sets are considered, set 1 consists of 50% of conventional soil, 5% of lime, 5% cement, and 40% CDW-2. Further from set 2 onwards, the conventional soil is replaced by 10% CDW-1 at regular intervals till set 6 which consists of 50% CDW-1, 5% of Lime, 5% of cement, and 40% of CDW-2. This mixture is further mixed thoroughly and subjected to sieve analysis to get sandy soil. Both the powders are subjected to sieve analysis as per the code specification [23] and as discussed by [6].OMC of the mix is obtained from the lab as per the code [24]. The block-making process involves batching, mixing, placing the mix, compaction, and ejection of the block [6]. Mardini block-making machine is used for the production of stabilized blocks, of size 230x190x100 mm. OMC is also confirmed at the site by making a ball out of the wet mix until a non-sticky mix is obtained as discussed by [6]. Calculated quantities of materials are poured into the mould of the Mardini block-making machine. The lid of the mould is closed and tightened and pressure is applied through the lever. The blocks are pushed out of the mould after completion of pressure application by opening the lid. Figure 2 illustrates the different stages of static compression. Figure 3 (a) and (b) show a manufacturing process of burnt clay bricks and unburnt clay bricks respectively.

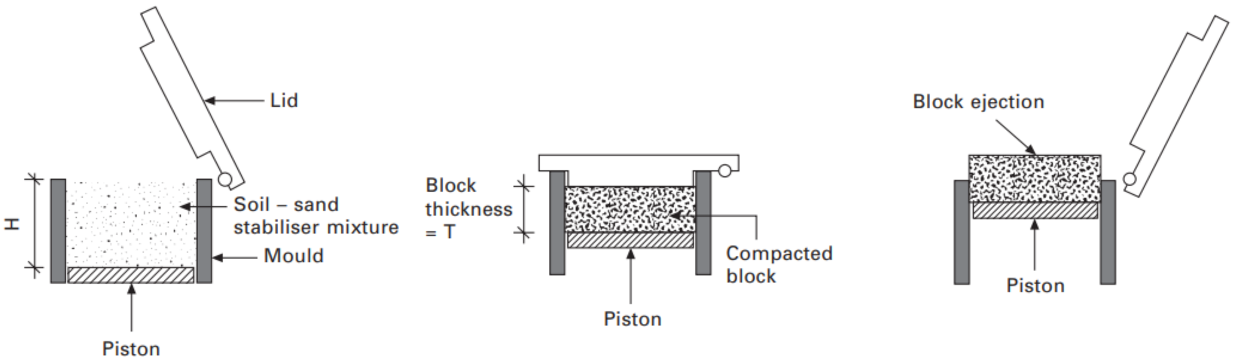


Fig. 2. Shows the various stages in the manufacture of blocks [1].

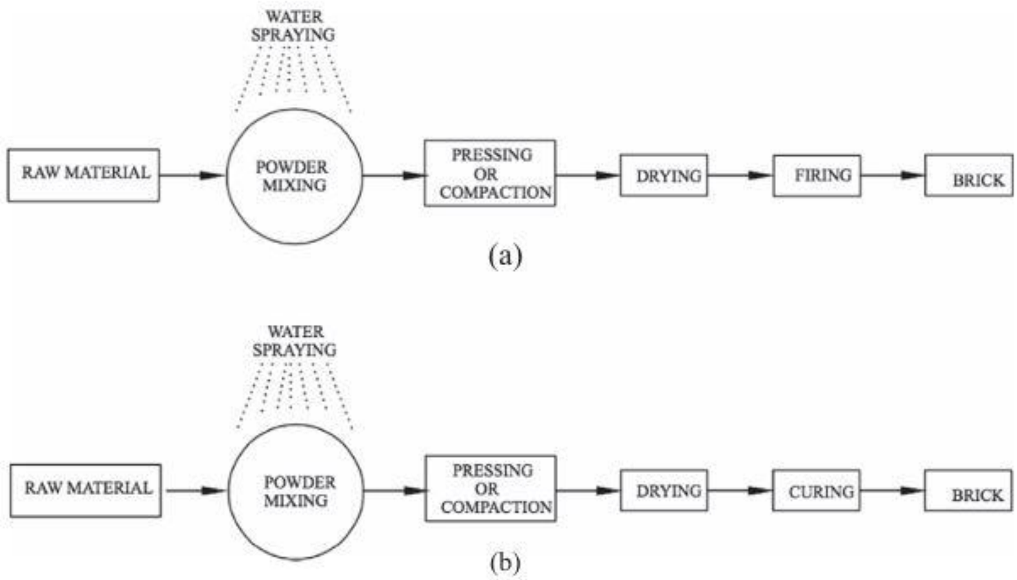


Fig. 3. (a) & (b): Shows the fired and unfired brick manufacturing processes respectively [1].

(a) (b) (c)

(d) (e) (f) (g)

Fig. 4. shows the manufacturing process of the Recycled Aggregate (RA) blocks. (a) Demolished Masonry is used in landfills. (b) Grinding of waste by road roller (c) Ground powder of CDW collected from nearby landfills. (d) Sieving and proportioning of RA. (e) and (f) Manufacturing of RA blocks using a manual compression machine. (g)Samples are cured by water spraying at regular intervals on the blocks.

The C&D[8] waste has been used as landfills in different parts of the world as no alternate practice is available to sustainably use this debris. Figure 4(a) shows the demolished construction waste dumped into an empty site. The debris from the landfills is collected, segregated, and powdered using an innovative method. Figures 4 (b) and (c) show the processing of this collected debris. The powdered debris is sieved using an IS 4.75mm Sieve. Figure 4(d) shows the result of sieving of the RA[9]. The processed RAs are proportioned and mixed with a binder and an optimum amount of water to cast the block. Figures 4(e) and (f) show the blocks cast from RAs and are cured for the age of 7, 14, and 28 days as shown in Figure 4(g).

4.1. Materials

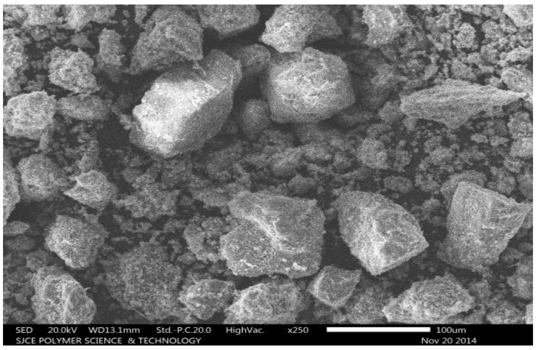
The following are the materials used in the present work.
CDW1:(Construction and Demolition waste 1) is composed of cement-based waste collected from nearby landfills, grounded by using the road roller available at the site.
CDW2:(Construction and Demolition waste 2) is composed of brick powder which is also collected from nearby landfills, grounded by using the road roller available at the site.
Lime: Class C lime is used as one of the binding materials as per the specifications in [25].
Cement: Ordinary Portland cement as per the specifications in [26] is used for the manufacturing of stabilized blocks.

[8] C&D- Construction and Demolition
[9] RA-Recycled Aggregate

Soil: The soil used in the manufacturing of stabilized blocks is sandy. The soil is selected from the nearby excavation sites as per the specifications mentioned in [27].
Figure 5 (a) shows the SEM image of CDW-1, which contains clusters of particles of different sizes that are mostly irregular. Figure 5 (b) shows the SEM image of CDW-2 showing highly irregular particles that are smaller in size when compared to that of CDW-1. Proper mixing of the two ingredients can result in a well-graded mixture that can contribute to the strength of the block. Figure 5 (c) indicates the SEM image of cement used as a binder in both Sample-1 and Sample-2, which consists of several particles of different sizes contributing to quick and continuous hydration.

Figure 5 (d) indicates the SEM image of lime used in the manufacturing of Sample-1 showing the distribution of tiny particles of varying sizes. CDW-1 and CDW-2 are materials having combinations of irregular particles of hydrated cement and filler particles, not contributing much to the workability of the mix, which is evident from the flow behaviour of CDW1 and CDW2. Figure 5 (e) shows the SEM images of soil particles that are unevenly distributed.

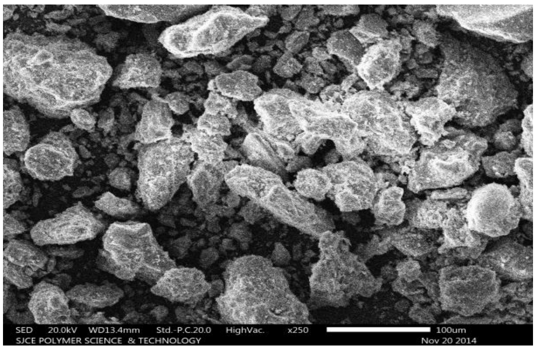

CDW1



SEM Image of CDW1

5(a): CDW-1

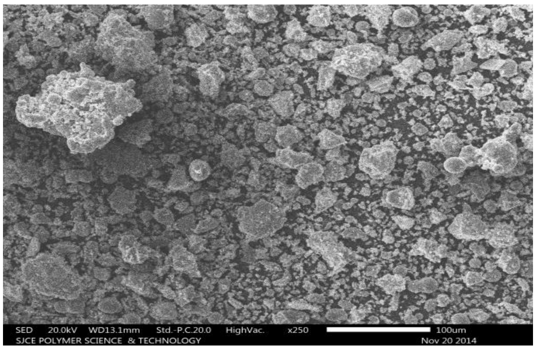

CDW2



SEM Image of CDW2

5(b): CDW-2

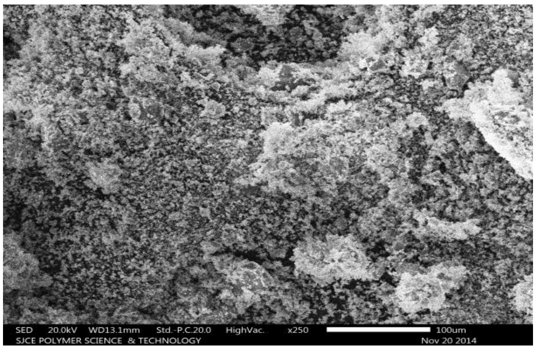

Cement



SEM Image of Cement

5(c): Cement

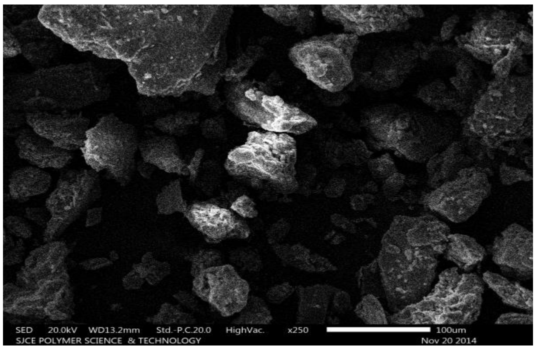
Lime



SEM Image of Lime

5(d): Lime

Soil



SEM Image of Soil

5(e): Soil

Fig. 5. shows the video camera and microstructure image (SEM) of different materials used namely (a) CDW-1 (b) CDW-2 (c) Cement (d) Lime and (e) Soil.

4.2. Mix proportioning

Table 1 presents the percentage composition of materials used in different mix proportions (S-1 to S-6) for manufacturing recycled aggregate blocks. Sandy soil content decreases gradually from 50% in S-1 to 0% in S-6, at a rate of 10% per mix. While CDW1 (Construction and Demolition Waste 1) increases from 0% in S-1 to 50% in S-6. The proportions of cement and lime remain constant across all mixes at 5% each. CDW2 (Construction and Demolition Waste 2) maintains a consistent 40% in all sets. The binding materials used in the mix, that is the 5% lime and 5% cement also maintained constant throughout. The binding materials percentage is obtained from the optimization achieved by [18] (Malkanthi et al., 2020) in their work. These variations in material proportions are designed to explore the effects of substituting sandy soil with CDW1 on the properties of the final product. Table 2 shows the density of each material used in the experiment. The materials are weighed and batched for the casting of blocks in accordance with the percentage and density of the material as shown in Table 3.

Table 1. Proportion of materials considered for different sets in percentage.

Sl No	Ingredients used	S -1(%)	S -2(%)	S-3(%)	S-4(%)	S-5(%)	S-6(%)
1	Sandy Soil	50	40	30	20	10	0
2	CDW1	0	10	20	30	40	50
3	Cement	5	5	5	5	5	5
4	Lime	5	5	5	5	5	5
5	CDW2	40	40	40	40	40	40

Table 2. Density of materials.

Sl No	Materials	Density(Kg/m^3)
1	Sandy Soil	1500
2	CDW1	1310
3	Cement	1440
4	Lime	2210
5	CDW2	1500

Table 3. Weights of the materials/block*.

SL NO	Sets	Sandy Soil (Kg)	C and Dwaste (Kg)	Cement(Kg)	Lime(Kg)	Brunt clay brickpowder (Kg)	Total Weight (Kg)
1	S-1	4.26	-	0.409	0.627	3.408	8.7
2	S-2	3.408	0.74	0.409	0.627	3.408	8.56
3	S-3	2.55	1.48	0.409	0.627	3.408	8.45
4	S-4	1.7	2.23	0.409	0.627	3.408	8.35
5	S-5	0.85	2.97	0.409	0.627	3.408	8.24
6	S-6	-	3.72	0.409	0.627	3.408	8.1

*Each block has a size of 230mmx190mmx100mm.

5. Experimentation and validation of results

The recycled materials are processed and used as a fractional or complete replacement of conventional materials to produce a new innovative product. The produced product shall be validated by adapting standard testing procedures employed for accessing the quality of the conventional materials and blocks. Some of the test procedures adopted by the researchers are discussed below.

5.1. Tests on materials

The materials used in manufacturing the blocks are subjected to different tests to affirm the properties similar to those of conventional materials. The major ingredient used in the manufacturing of the SMB[10] is soil. The soil used in the manufacturing of the unfired blocks should have a gradation of sand, silt, and clay contents, and are normally in the range of 36–82%, 12–34%, and 6–30%, correspondingly as mentioned by [1] [6], it was also found that there is constantly the best clay content present in the soil used in the blocks as discussed by [28]. To confirm this gradation the sieve analysis test is carried out. To study the most suitable binding material for the manufacturing of blocks two major binding materials in the form of cement and lime are selected and a cube compressive strength (CS) test is carried out as mentioned by [29]. The OMC of the RA and the soil are determined as done by the researchers [30] as per the code [24]. The specific gravity of the CDW was determined as mentioned in [5]. (Venkatarama Reddy and Gupta, 2006) [31] discuss the use of alternate fine aggregates in the preparation of mortar used in the production of structural masonry, the workability of the mortar is ensured by conducting a flow table test. The blocks manufactured should be confirmed to the dimension of the blocks mentioned in the code [1], the influence of the density of the block and CS is considered [18] and the block density was found. Water absorption of the blocks plays a pivotal role in the early stages of the construction of masonry. It is desired for the blocks to have lesser water absorption as they should not absorb more water from the fresh mortar, water absorption test is carried out as discussed by [16], and the CS of the block was tested as discussed by [32] and the impact of various parameters on the CS of the blocks was studied. The

[10] SMB- Stabilized Mud Blocks

microstructural analysis is carried out on the test samples to study the behaviour of the ingredients used in the manufacturing of the blocks and this helps in the determination of the best binding material and their chemistry with the RA [33]. Prism strength on masonry was tested in confirmation with the ASTM-c1314 as discussed by [34].

5.2. Sieve analysis

Based on extensive research done by researchers, proper classification has been shown to increase bulk density, which improves CS [35]. A mechanical sieving machine (2,40, 1,00, 0,60, 0,30, 0,15, and 0.075 millimeters) was used to analyze the particle size of CDW as discussed by [13]. Venkatarama Reddy et al., 2007 [36] refers to an experimental study on how soil particle size affects the earth-cement shear strength and mass properties. Researchers believe the sieve analysis is suitable as a baseline test in experimental soil analysis for grading purposes. The sieve analysis is carried out as per the procedure laid out in [23]. Table 4 shows the results of the sieve analysis carried out on the CDW-1 and CDW-2. The particle size gradation curve for the two types of CDW is shown in Figure 5. From the graph, it can be observed that in CDW-1, the percentage of gravel is 5.9%, 88.6% of sand and fine is 5.5%. CDW-2 consists of 7.2% of gravel, 91.6% of sand, and 1.2% of fines. Figure 6 shows the particle size distribution curve for various RA used with limits.

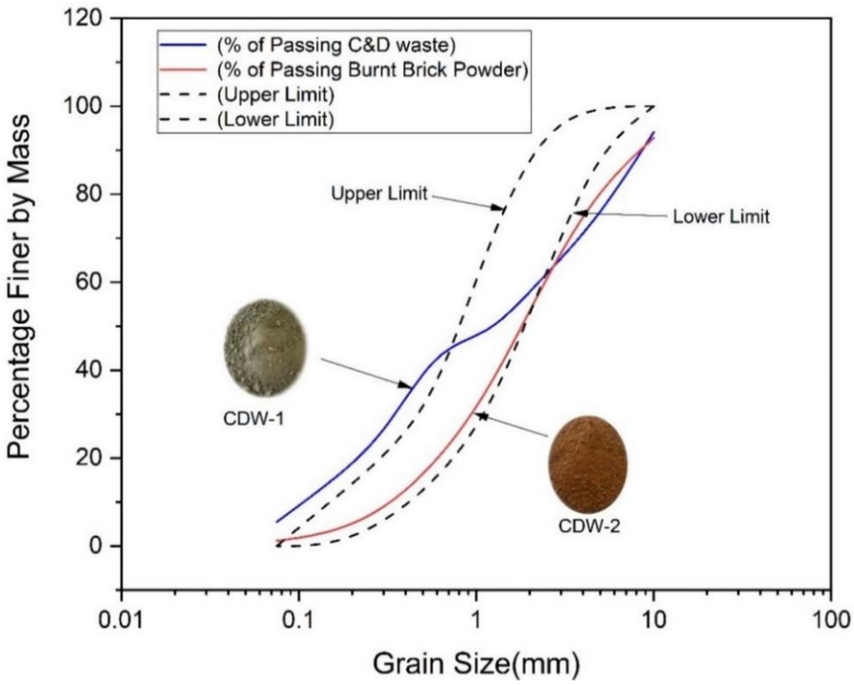


Fig. 6. Particle size distribution curves.

Table 4. Properties of Recycled Construction Materials.

Properties	Type of Materials	
1. Textural Composition (%)	CDW-1	CDW-2
Gravel	5.9	7.2
Sand	88.6	91.6
Silt+Clay	5.5	1.2
2. Atterberg limits		
Liquid Limit (%)	46	51
Plastic Limit (%)	27	23
Plasticity Index	18	27

5.3. Optimum moisture content [OMC]

The OMC of the soil is determined as per the specifications in [24]. The dry density of sample-2 was 19.63 KN/m^3 and the OMC was 10.4%, corresponding to the maximum point on the moisture content/ dry density curve. Figure 7 shows the Moisture content vs dry density curve for sample 2.

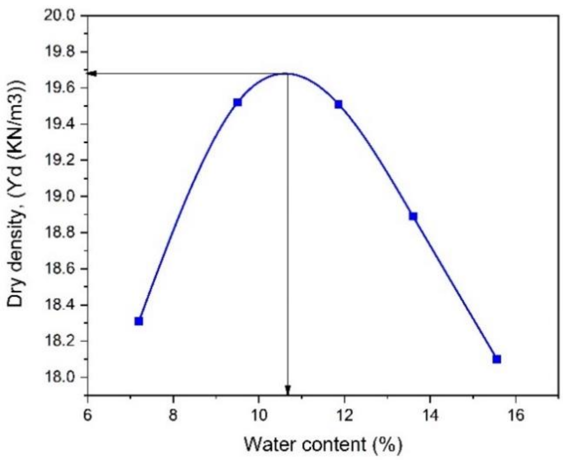


Fig. 7. Moisture content vs dry density curve for sample-2.

5.4. Compressive strength

One of the earliest types of testing for construction materials is the compression strength of masonry because of the long history of masonry as a structural system [34]. CS test is done to obtain the resistance of the blocks against compression load, the blocks are placed between the lower and middle jaw of the UTM[11] or Lower and upper jaw of the CTM, and the compression loads are applied at a specific rate to obtain the result. The dry and wet strength of the blocks were evaluated at 7, 14, and 28-day age of curing of blocks. For the wet CS test, the 7, 14, and 28 days cured blocks were taken and submerged in potable water for 48 hours. The blocks were subjected to dry CS as per the procedure in [37] [38]. According to this the maximum breaking load in "N" divided by the average net area in (mm^2) of the two compression sides yields the CS. Five blocks of each type were tested as mentioned in [39], and the block's CS was determined by averaging the results. Figure 8 shows the dry CS test conducted on various sets of blocks.

(a)Block placed in compression testing machine.

(b) Failure pattern of the tested specimen.

Fig. 8. (a)&(b): Compression strength testing of blocks.

[11]UTM- Universal Testing Machine

Set 6 which is the mix consisting of 50% CDW-1, 5% cement, 5% Lime, and 40% CDW-2 showed the maximum CS of 2.82 MPa at 28 days age of curing. The CS thus obtained is less than the minimum strength necessity as per [40] (IS 1725: 2023), therefore the average CS of the innovative blocks could not meet the minimum strength requirement as per [40] (IS 1725:2023). The mix proportion with maximum CS that is set 6 is considered for modification. Set 6 is modified by increasing the cement content from 5% to 10% and decreasing the lime content from 5% to zero in the mix. Thus, the new mix formed consists of 50% CDW-1, 10% cement, and 40% CDW-2, again the blocks with the new mix proportion were cast, water-cured, and tested for 7, 14, and 28 days of age of curing for CS. Interestingly the new blocks produced a CS of 2.72 MPa at 7 days of curing which is a 171% increase, CS is 3.31 MPa at 14 days of curing which is a 155 % increase, and CS is 6.82 MPa at 28 days of curing which is 242% increase. Figure 9 shows a graph of results for the CS test on blocks with percentage variation of CDW-1, Figure 10 shows the comparison between the two blocks that are set 6 and modified set 6. Figure 11 shows the histogram of the increase in strength of blocks with age. From this comparison, it is evident that the type of binding material and percentage of binding material added to the manufacturing of RA blocks play a vital role.

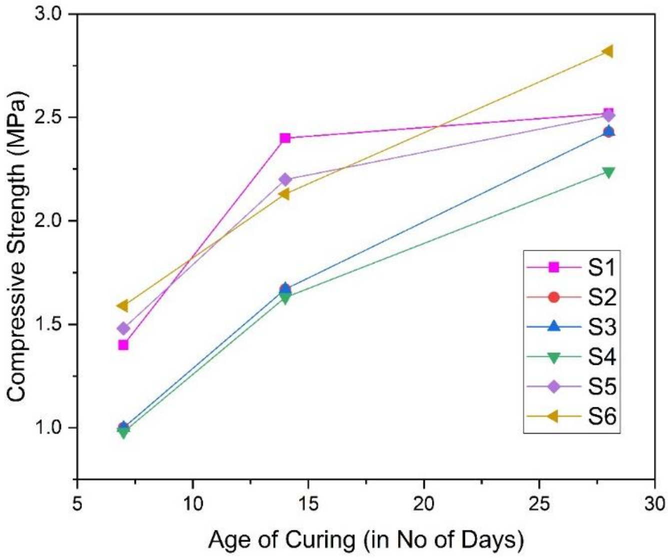


Fig. 9. Graph showing the number of days versus CS in MPa.

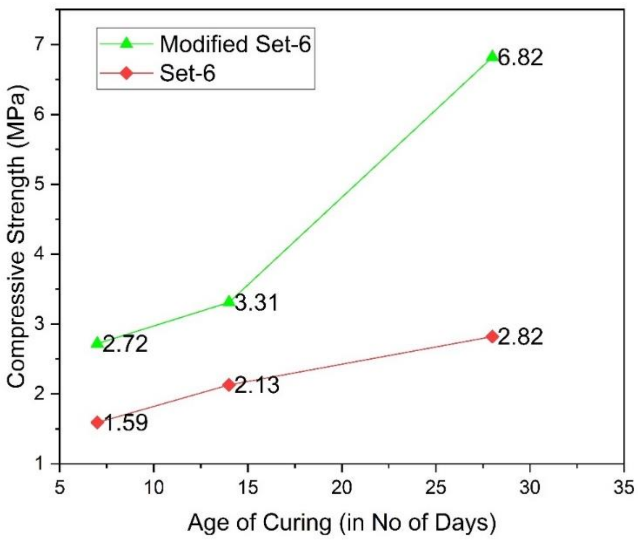


Fig. 10. CS of modified set-6 blocks at 7, 14, and 28 days of curing.

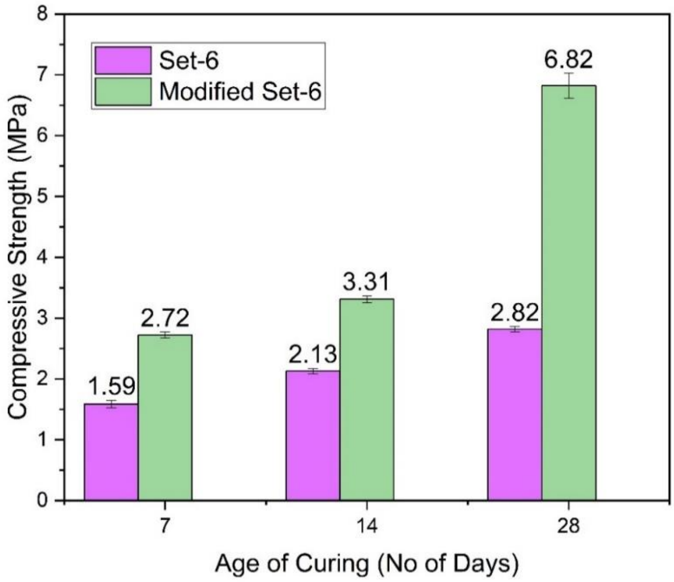


Fig. 11. Comparison of CS between Set 6 and modified Set 6.

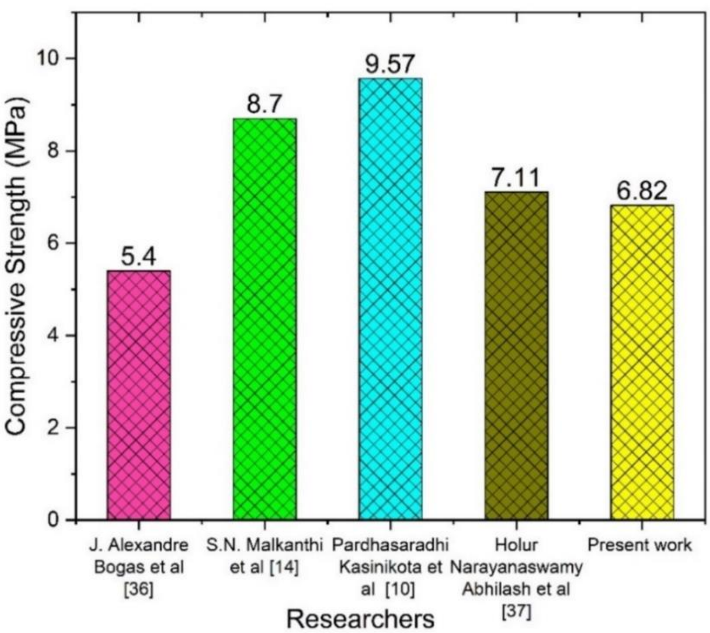


Fig. 12. Comparison of compressive strength of stabilized blocks made of CDW.

CS of contemporary works of various researchers working with CDW as the recycled aggregates for stabilizing blocks are compared. Bogas et al., 2019 [41] adapted a mix with 8% cement, 15% RA, and 80% soil to produce stabilized blocks with CS 5.4 MPa and water absorption of 13.6%. 10% cement was mixed with CDW to obtain stabilized blocks of 8.7 MPa with water absorption of 11.1% by Malkanthi et al., 2021[15]. Kasinikota and Tripura, 2021 [11] mixed 76% Soil-sand, and 24% Crushed brick waste with 10% cement to produce the blocks with CS 9.57 MPa and water absorption of 10.52%. Abhilash et al., 2020 [42] added 10% cement and CDW to produce the blocks of CS 7.11 MPa and water absorption of 13.11 %. In the present work, 10 % of cement is added with two types of CDW that is CDW-1 and CDW-2 to obtain the blocks with CS 6.82 MPa, which can be improved with further research. The low water absorption of 10.46 % when related with other works. Figure 12 shows the comparison of CS test results for stabilized blocks made with CDW by various researchers. Figure 14 shows the comparison of water absorption results of various researchers for the blocks made of CDW.

5.5. Water absorption

According to IS code [37], the test for water absorption is performed. In this test, the oven-dried blocks are weighed for their initial weight and immersed in water for 24 hours, after this period blocks are taken out and weighed for their final weight, the percentage of increase in weight should not be more than 20% of the initial mass of the block. This test is run to ascertain the brick's ability to absorb water and how quickly it absorbs moisture with the time they are submerged in water. The blocks were weighed once more after 24 hours, and an upsurge in mass indicating water absorption was noticed [16]. In the present work, the average water absorption of the modified blocks was found to be 10.46% which is less than the maximum water absorption permitted for a masonry unit which is 15% as per [40]. This shows that the modified RA blocks absorb less water from the fresh masonry mortar. Figure 13(a) shows the oven drying of the blocks. Figure 13(b) shows the blocks placed submerged in water.

(a): Oven drying of block.

(b): Block immersed in water.

Fig. 13. Water absorption test on RA stabilized block.

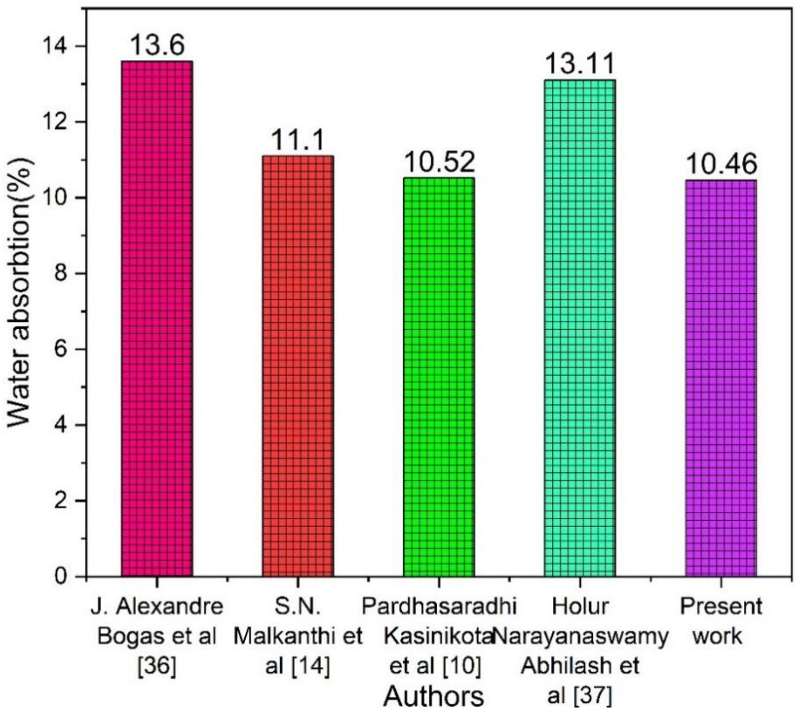


Fig. 14. Comparison of water absorption results of various researchers for the blocks made of CDW.

5.6. Dimension test on blocks

The length, width, and height of the selected samples of non-modular blocks of dimension 230 mm in length, 190mm in width, and 100mm in height are measured as per [39] And [40]. Measurements of individual dimensions of each sample are read to the nearest scale division. The length is measured from the longitudinal center line of each surface, the width of the upper and lower bearing surfaces is measured at the average width, the height is measured from all four vertical surfaces at the average height, and the average is recorded. Each sample's average length, width, and height are reported to the nearest 0.5 mm as shown in Table 5. Figure 15 (a) (b) (c) shows the dimension of the casted non-modular block.

(a) (b) (c)

Fig. 15. (a) (b) (c): Shows the Length, Width, and Height of the non-modular block as 230mm, 190mm, and 100mm respectively.

5.7. Density of the blocks

Three Stabilized blocks of Modified set-6 were randomly selected from the sample and the blisters and loose particles were removed from the surface. The length, width, and height of each block were measured using steel tape, and the volume of each block was calculated with the measured dimensions. Then each block was weighed using a kilogram weighing balance to the adjacent 10g. Hence the density of a block was calculated using the formula below, and the average density of three blocks was determined as per [40]. The dry density, of the block determined, is 1820.67 kg/m^3, which is superior to the minimum dry density requirement of 1750 kg/m^3 as per [40]. The measurements are shown in Table 5.

$$Dry\ Density = Mass\ of\ the\ specimen, kg / Volume\ of\ the\ specimen, m^3$$

Table 5. Density of stabilized mud blocks.

Sl. No.	Length, mm	Breadth, mm	Height, Mm	Weight, kg	Volume, mm^3	Unit weight in kg/m^3
1	232	190	110	8.460	4848.8x10^3	1744.76
2	231	192	100	8.421	4435.2x10^3	1898.67
3	230	191	100	8.100	4393.0x10^3	1843.84
Average Block Density = 1829.09 kg/m^3						

5.8. Efflorescence test on blocks

The efflorescence test was carried out on the recycled aggregate block in the laboratory, five blocks were selected and placed in a plastic tray of size 180mmX180mmX40mm. One end of the block is immersed in the tray filled with water. The depth of immersion is 25mm, and the entire setup is placed in a laboratory whose temperature is maintained at 20 to 30^0 C until the water in the tray is absorbed, the reduced water level is refilled after 24 hours up to the mark of 25mm, and the blocks are once again allowed to absorb the water, for another 24 hours at the end of 48 hours the blocks are examined for the formation of efflorescence, the result indicated a.)Nil as per [37] . Figure 16 shows the test setup for the blocks placed for efflorescence.

Fig. 16. Test setup for the blocks placed for efflorescence.

5.9. Tests on mortar

The CS of the mortar mixed in the ratio of 1:4 is obtained by testing 70.7x70.7x70.7 mm cube specimens after a 28-day age of curing. The average of the three tested cubes is reported as the CS of the mortar as advised in [43] [44]. Figure 17 shows the CS test conducted on the RA mortar cubes. An average CS of 19.47 MPa was recorded after a curing period of 28 days. According to the standard, a flow table test is used to determine the consistency of the grout [44] [31]Figure 18 shows the flow table test on fresh mortar. For the water-cement ratio of 0.7, 0.9, and 0.95, respectively, flow values of 80, 95, and 105 were observed. The specimens have failed by splitting/Vertical splitting rather than conical shear.

(a) Mortar cubes for compression test.

(b) Demoulded cubes of size 70.7 mm.

(c) Cube placed in test setup.

(d) Nature of failure of the tested specimen.

Fig. 17. (a)(b)(c)(d): CS test on mortar cubes.

Fig. 18. Flow table test and nature of flow of mortar.

6. Microstructural analysis

6.1. SEM (Scanning electronic microscope) with EDS (Energy-dispersive xray spectroscopy)

SEM Images are used to analyze the microstructure of the ingredients used in the current investigation, in addition to their textural behaviour [45]. The morphological characteristics of stabilized blocks processed from recycled aggregates in combination with two types of binders namely cement and lime (sample-1) and cement alone (sample-2) were analyzed. The samples taken from blocks cured for 28 days are ground and analyzed.

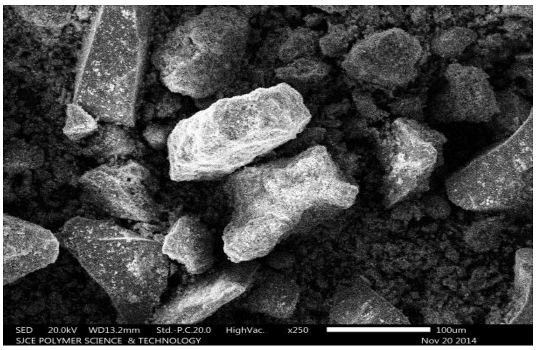
Figure 19 (a) shows the SEM image of sample-1 containing particles of CDW-1 and CDW-2, which are combinations of coarser and finer particles of fillers and binders. Figure 19 (a) shows that the amount and distribution of CSH gel are insufficient to fill the pores, leading to a large amount of porosity and resulting in reduced CS of the blocks. Figure 19 (b) shows the SEM image of sample 2 which confirms the increase in adhesion between cement paste and recycled aggregate which is due to the formation of hydration products such as CSH, Portlandite, and Calcite around the aggregate. Here we noticed a higher percentage of finer materials of cement surrounding the coarser particles which are filler in nature. The same is reflected in XRD data as well.

EDS (Energy-Dispersive Xray Spectroscopy)

The EDS shows the higher content of major peaks of Ca, Si, and O, indicating calcium silicate hydrates (CSH) in both blocks.

The Ca:Si ratio of sample-1 and sample-2 were calculated from the values shown in Figures 20(a) and 20(b). At 28 days of curing Ca:Si ratios are 0.62 and 0.89 for samples 1 and 2 respectively, and the higher ratio of Ca:Si of Sample 2 may have led to a higher concentration of CSH gel, which has resulted in enhanced CS as discussed by [46] (Joseph et al 2022).

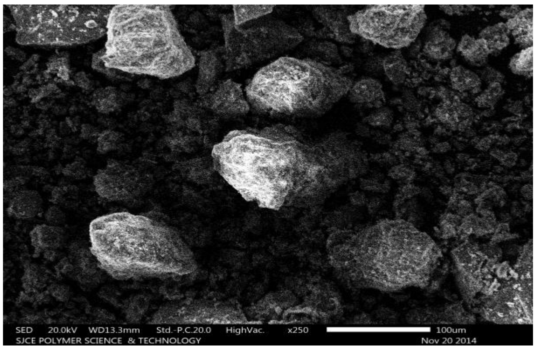
Sample-1



SEM image of Sample-1

(a): Sample-1

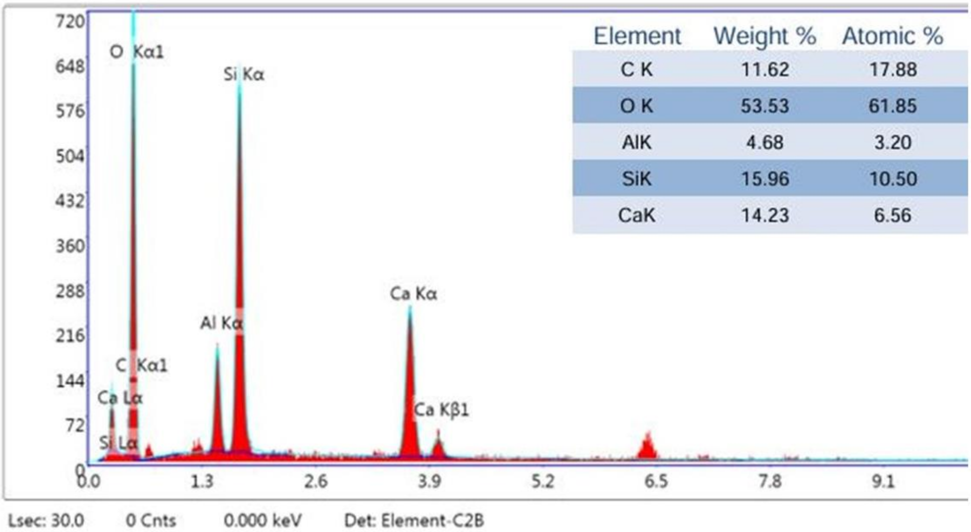
Sample-2



SEM image of Sample-2

(b): Sample-2

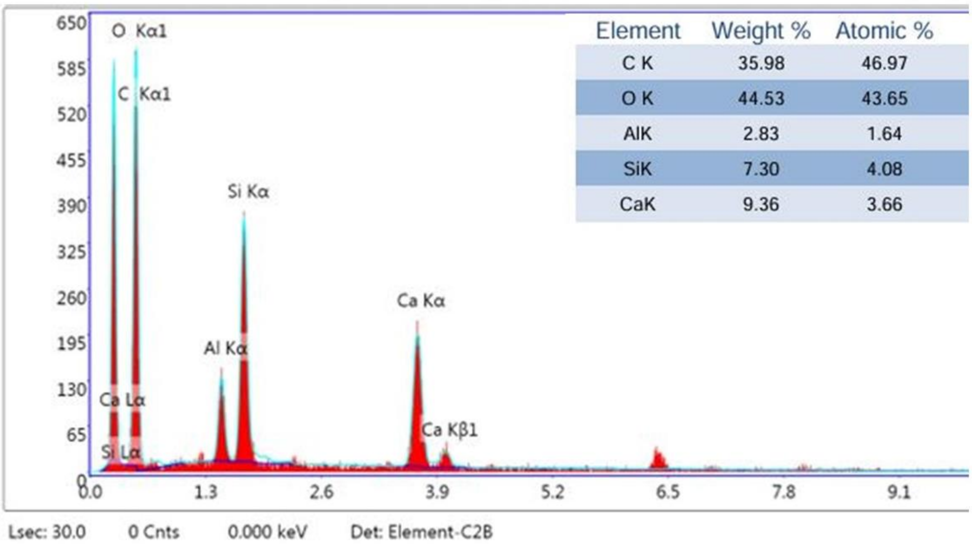
Fig. 19. Shows the microstructure image (SEM) of different materials used that is.



Element	Weight %	Atomic %
C K	11.62	17.88
O K	53.53	61.85
AlK	4.68	3.20
SiK	15.96	10.50
CaK	14.23	6.56

(a) Sample-1 (b) Sample-2

Fig. 20. (a): EDS Analysis of Sample-1.



Element	Weight %	Atomic %
C K	35.98	46.97
O K	44.53	43.65
AlK	2.83	1.64
SiK	7.30	4.08
CaK	9.36	3.66

Fig.20. (b): EDS Analysis of Sample-2.

6.2. XRD (X-ray Diffraction)

Determining the primary mineral/crystalline phases found in the RA and the finished unburnt RA stabilized block is a crucial step in identifying the behaviour of ingredients in the masonry. In this case, XRD provides precise information about the unburnt block's crystalline phases and their initial raw material [47]. Figure 21 shows a graph of XRD data plotted considering 2θ(degrees) VS Intensity (a.u.).

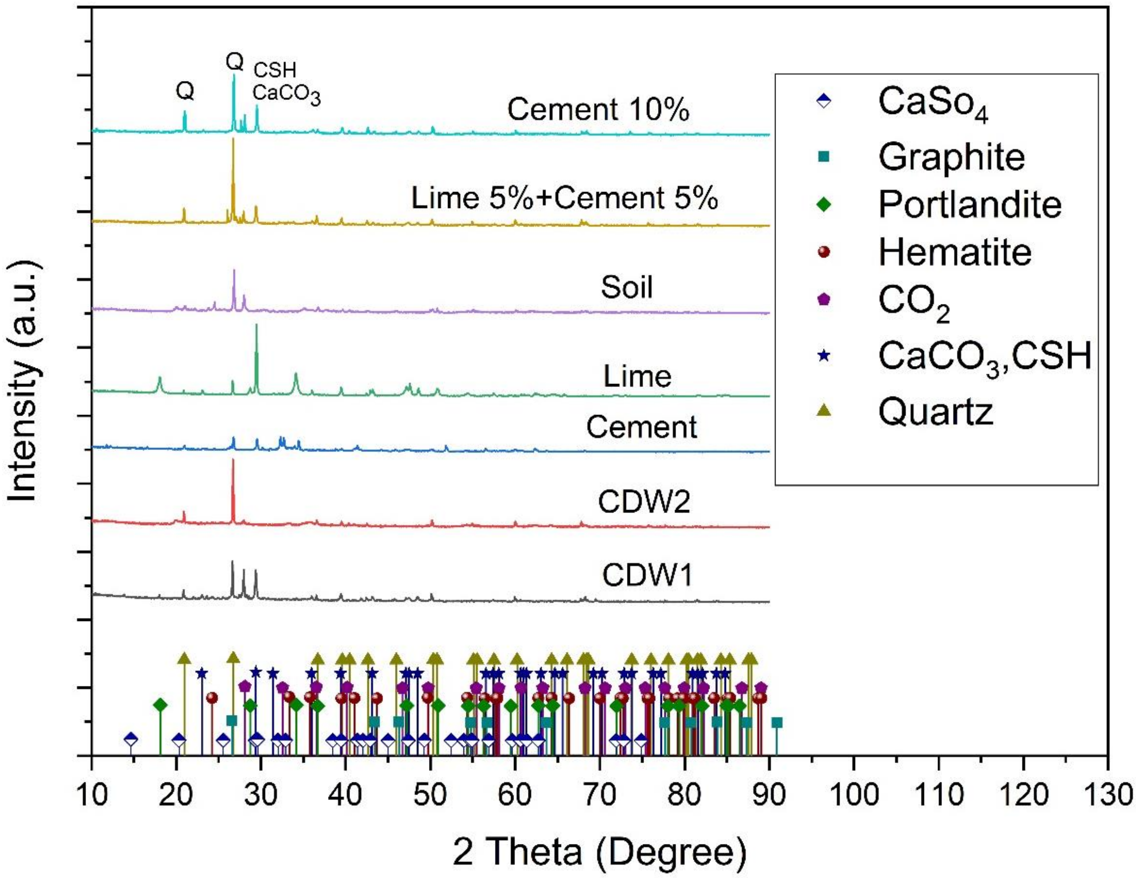


Fig. 21. A graph of XRD data plotted considering 2θ(degrees) VS Intensity (a.u.).

XRD analysis of Five base materials and two samples was carried out on the ground samples. The XRD data thus obtained is used for phase identification using the commercial software X'pert High Score, which revealed the presence of several chemical constituents compared to the database. The predominant chemical components at 2θ=29.5^0 and 2θ=27^0 are Lime and Quartz respectively [48]. On analyzing the CDW1, the peaks at different 2θ values indicated the presence of Quartz, CSH, Portlandite, and Carbon. A similar observation of peaks in CDW2 revealed the presence of a substantial amount of quartz, which indicates the presence of clay-based material used in burnt clay brick. More noise is observed in the case of cement as it is un-hydrated cement. The peaks corresponding to lime indicate the presence of portlandite and a substantial amount of calcium silicate hydrates. The peaks corresponding to soil indicate the presence of quartz along with small quantities of carbon and similar peaks are noticed in CDW2 as it is derived from burnt clay bricks. The Peaks observed in sample-1 and Sample-2 are almost similar, but a slightly higher peak at 2θ value 29.5^0 in Sample 2 indicates the presence of a higher concentration of hydration products namely CSH overlapped with calcite [46][49], which has contributed to higher strength. The same is reflected in SEM images in Figures 19 (a) and (b).

6.3. FTIR [Fourier Transform Infrared Spectroscopy]

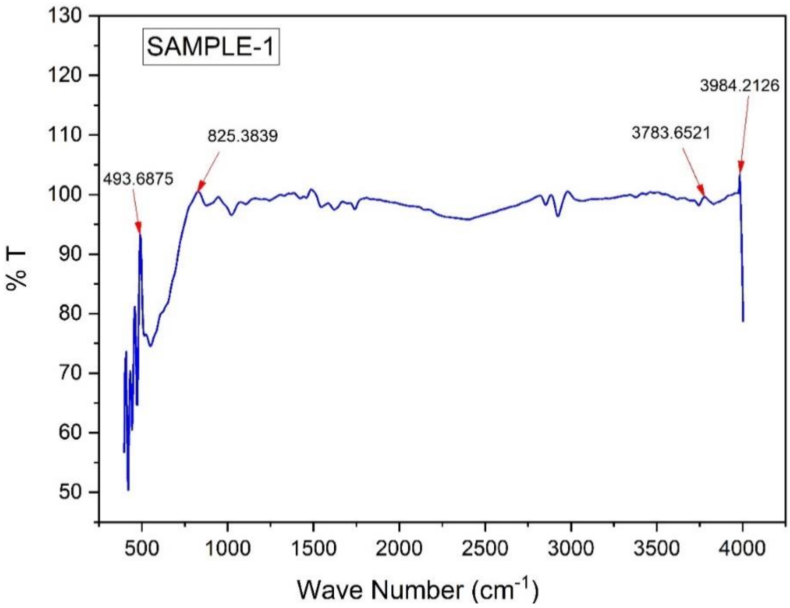


Fig. 22. (a): FTIR Peaks for Sample-1.

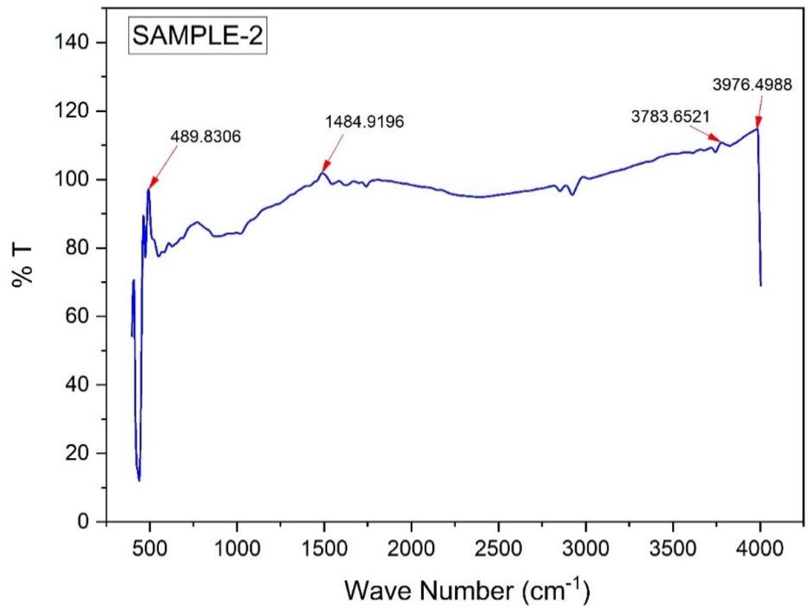


Fig. 22. (b): FTIR Peaks for Sample-2.

Figures 22(a) and (b) represent the FTIR results of samples 1 and 2 respectively. Figure 22 (a) shows flat lines, and Figure 22(b) shows lines of more variation indicating the presence of Phenol as the functional group around the 3587(cm^{-1}) frequency range. and the presence of O-H stretching vibration around 3854 (cm^{-1}) [50]. Prasad and Ravande, n.d. [51] observed that the peak at 493.68 (cm^{-1}) in Sample-1 and 489.83 (cm^{-1}) in Sample-2 shows the presence of a strong bond of Si-O, Al-O indicating the formation of CSH. However, the presence of O-H Stretching vibrations of $Ca(OH)_2$ in sample 2 is responsible for the increase in its strength as compared to sample 1. The same result is reflected in the XRD analysis.

7. Durability study on blocks

There exist several methods of test to determine the durability or the weather resistance of the blocks. various methods have been adapted by researchers over the years to study the durability characteristics of stabilized blocks. Durability tests on blocks are broadly classified into two main categories first type is accelerated which includes tests like the Spray test, Drip test, Rainfall test, and Slake test. The second type is indirect tests and includes tests like Wire brush test, Wet dry strength ratio, Capillary water absorption test, Total water absorption test, Water absorption test under static pressure, and Freeze-thaw cycle test [52]. An accelerated erosion test was carried out in the laboratory by [53] Arooz and Halwatura, 2018, found that weathering had no significant effect on the mud concrete blocks. A study on the impact of compaction on the durability of the blocks by conducting tests like abrasion and absorption coefficient [54]. It is also suggested to use recycled aggregate concrete in chloride and sulfate-prone environments [55].

The most common test used by several investigators is the wire brush test [20]. The same is discussed in the Bureau of Indian Standards and the same procedure is followed in this investigation. Here the modified blocks were subjected to a weathering test as per [40] to ensure their durability [56]. Three blocks were selected randomly, the specimen was dehydrated in the oven at 65^0 C for 2 hours, and each specimen's initial mass was noted. The specimens are then soaked in water for 5 hours and dried in the oven at 75^0 C for 42 hours. All six faces of the specimen are scratched twice with the wire brush, by holding the longer axis parallel to the longitudinal axis of the specimen and applying the firm strokes corresponding to 15N as shown in Figure 23**,** thus completing one cycle of weathering test. The above procedure is repeated 12 times to complete 12 cycles. At the end of 12 cycles, the specimens were dried in an oven at 65^0 C and weighed at intervals of 2 hours, which showed less than 0.05 percent variation in mass. From this, it is concluded that the blocks are weather-resistant.

Fig. 23. Samples considered for the weathering test and measure of applied pressure by wire brush scratch.

8. Prism test

Mud blocks with three and five numbers are stacked on top of one another to test prisms. This test was conducted after 28 days age of curing, to determine the mass efficiency and prism strength for the 3 and 5-block models [57]. The bending strength was Measured using prisms stacked with four blocks in a study carried out by [58]. A controlled displacement was used to test the prism before testing, half of them were submerged in water for 48 hours. CS was determined at a loading speed of 0.61 mm/min. The fracture geometry of the fractured specimen was noted along with the final breaking load. Prism strength was found lesser than that of mortar or other materials tested separately, as in conventional masonry [34]. Theoretically, the formulas also predict the prism's CS [59]. The rupture modulus, referred to as the maximum amount of bending stress that a material can withstand is known as its flexural strength [57]. In the present work, the blocks with a maximum CS that is modified set-6 were used to construct masonry prisms of five blocks and allowed for a curing period of 28 days, these masonry wallets were tested for dry CS by applying axial loading. The masonry prism showed an average CS of 1.68 MPa, 2.74MPa, and 4.1MPa after 7, 14, and 28 days of curing. From Figure 24(c) it can also be observed that the masonry prisms failed by splitting with vertical cracks, the failure of masonry is mainly based on strain compatibility at the masonry units-mortar interface. Masonry strength increases with block strength and mortar strength [59]. Figure 24 shows the test setup to conduct the prism CS test. (Manjunath S. Amalkar et al 2021) [60] in their work, it is suggested that a block strength in the range of 7.03MPa to 10.91 MPa, and prism compressive strength in the range of 2.78 and 4.82 MPa, shall be comfortably used as load-bearing material for a 3-storey building.

(a): Masonry prisms made of masonry blocks in the casting yard.

(b): Testing of Specimen in compression testing machine.

(c): Nature of failure.

9. Cost analysis

Table 6 shows the cost analysis for the casting of recycled aggregate blocks in the laboratory. Thus, it costs 53.5 rupees in the laboratory to manufacture one stabilized recycled aggregate block. The cost of conventional stabilized mud blocks of similar dimensions (230mmx190mmx100mm) is around 30 to 35 rupees, with an increase of about 40%. This can be attributed to the first three items namely 1) Cost of labour for collection, segregation, and loading of CDW at the source point 2) Transportation of CDW to the laboratory 3) Processing of CDW (converting it into powder) with the help of a road roller. However, the cost of mass production of the blocks is reduced due to the standardization of equipment, discounts on materials on bulk purchases, and reduced transportation costs. The increase in cost by 40% is quite bearable considering the several advantages in the form of reduced environmental pollution risk, reduced landfills, and reduced usage of natural materials such as river sand and fertile topsoil.

Table 6. Cost analysis for the casting of recycled aggregates stabilized blocks in the laboratory.

Sl. No.	Item Description	Unit	Quantity	Rate (INR) Rs.	Total (INR) Rs.
1.	Cost of labour for collection segregation and loading of CDW at the source point	No.	2	500	1000
2.	Transportation of CDW to the laboratory.	Lump sum	1	500	500
3.	Processing of CDW (converting it into powder) with the help of a road roller.	m^3	1	400	400
4.	Sieving of powdered CDW to useable sandy soil form (4.75mm sieve)	m^3	1	1000	1000
5.	The casting of blocks (assuming that 1 Mason and 2 Helpers cast about 50 blocks per day manually, 230 blocks can be cast from a cubic meter of CDW). To cast 230 blocks, 4.5 masons and 9 helpers are required.				
	Mason	Nos.	4.5	800	3600
	Helper	Nos.	9	500	4500
6.	Cement	No. of bags	2	400	800
7.	Curing of blocks for 28 days requires one helper on a lump sum basis	Lump sum	1	500	500
	For casting of 230 blocks in one Cum of CDW				12300
	For casting one block of CDW, the cost is				53.5

10. Conclusion

In the current work, the properties of recycled aggregate for the manufacturing of stabilized blocks have been studied. The mechanical, physical, and microstructural characteristics and durability of the recycled aggregate stabilized blocks are investigated, in addition to the application of the blocks in masonry. The following conclusions are made from the results of the investigation.

- The study evaluated the use of recycled aggregate which is derived from masonry waste dumped in and around the city landfills, as a sustainable alternative to the fine aggregate in the manufacturing of the stabilized earth blocks.
- Among the various combinations considered, the one with 50% CDW-1 and 40% CDW-2 mixed with 5% lime and 5% cement gave a maximum CS of 2.82MPa at 28 days. This CS was below the minimum requirement of 3.5 MPa as per the standards for stabilized mud blocks.

- The CS of the modified block having 10% cement showed a 28-day CS of 6.82MPa, an increase of 242%. This modified block can be designated to Class-5 as the average CS is greater than 5MPa.
- Modified set-6 showed good properties, namely water absorption of 10.46%, average density of 1820.67 kg/m^3 and having no efflorescence.
- Microstructural analysis of the materials was carried out to examine the nature of the ingredients used and the SEM images with EDS revealed that the strength of the modified block is due to the proper binding of finer particles around the coarser filler materials.
- XRD analysis carried out on the materials used in the block shows the presence of constituents such as Quartz, CSH, Calcite, Hematite, Portlandite, Graphite, and $CaSO_4$, through crystalline peaks. The presence of higher peaks indicating CSH and Portlandite in sample 2 is the main cause for the strength of the block. FTIR analysis shows the presence of hydrated compounds in the case of sample 2 which reflects the strength of blocks.
- The durability of the blocks was found to be good after the 12 cycles of wetting, drying, and scratching tests.
- The prism pallets of five blocks as masonry, when subjected to axial compression, gave an average strength of 4.1 MPa at 28 days, which can be used in structural applications, leading to sustainable construction.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Monish Kumar K: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Software; Supervision; Validation; Visualization; Roles/Writing – original draft;

Thanu H P: Formal analysis; Investigation; Project administration; Supervision; Validation; Visualization; Writing – review & editing.

Nataraja M C: Formal analysis; Investigation; Supervision; Validation; Visualization; Roles/Writing – original draft; Writing – review & editing.

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