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EXPLORING CIRCULAR BUILDING MATERIAL: TRANSFORMING INDUSTRIAL AND AGRICULTURAL WASTE INTO 3D PRINTABLE CONSTRUCTION MATERIAL

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ABSTRACT

Clothing is one of the basic needs of mankind. The textile industry produces the large amounts of fabric waste threatening the environment and contributes to a significant percentage of non-biodegradable waste. The massive amounts of textile waste dumped in landfills have led to growing environmental issues, which have forced the textile and fashion industry to adopt and practice sustainable waste management and disposal solutions. Recent research has shown that varieties of textile wastes, including pre- and post-consumer, may be treated and used successfully in building operations. This research paper aims to investigate the possibilities of using industrial textile waste and agricultural waste—specifically, textile residues of cotton fabric and cow dung that can be converted into environment friendly building materials. This research was conducted in two phases. The first phase included developing a mix using fabric waste to employ 3D printing technology. The material mix achieved in the first phase of several experiments was 3D printable. However, it was high density material and was unsuitable for light weight construction. The second phase involved to achieve a mix for lightweight blocks by replacing red soil with cow dung. The second phase achieved promising results to achieve lightweight blocks using fabric and cow dung. The findings of this study will help formulate experimentation techniques and methods to develop novel composite as well as sustainable material which could be adopted in the building construction.

Keywords: *3D Printing; Cow-dung; Compressive Strength; Sustainable Blocks; Textile Waste.*

1. INTRODUCTION

In recent decades, the building industry has experienced substantial growth, which has led to a rise in its adverse impact on the environment. Traditional and contemporary building materials consume an enormous amount of energy and virgin material resources in their manufacturing processes. Sustainable Development Goal 12 'Responsible Consumption and Production' aims to address natural resource consumption by promoting sustainable practices across the entire production and consumption cycle (United Nations, 2023). The construction sector needs to adopt sustainable consumption patterns and minimize the resource depletion by maximizing the use of recycled building

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materials. This highlights the importance of innovative building materials in minimizing the use of virgin resources and enabling the reuse of waste generated not only by the construction sector but also by other industries. The use of composite materials in construction has currently had a significant impact on achieving environmental sustainability.

Several researchers have explored different ways to incorporate industrial wastes for manufacture masonry blocks. The industrial wastes such as fly ash, textile effluent treatment plant sludge, polystyrene foam, plastic fibre, rice husk ash, wood sawdust and limestone dust, and processed waste tea have been used in the production of building materials (Mandavgane et al., 2011). To meet the urgent need for environmentally friendly substitutes, this study investigates how industrial and agricultural waste can be converted into environmentally friendly building materials. This innovative approach aims to repurpose waste streams into useful resources to minimize the ecological imprint of construction activities and promote the concepts of the circular economy within the built environment. The findings of this study will help to develop novel composite material which could be adopted in the building construction.

2. LITERATURE REVIEW

Textile waste fibres have potential application in architecture and construction industry. Reusing waste textiles for construction is one of the most durable methods of long-term recycling or prolonging the life cycle of textiles (Nistorac & Loghin, 2023). Previous studies have demonstrated that recycled textile waste can be effectively used as building material. Textile fabrics have multiple applications in construction including thermal insulation panels or blankets, as resistance components such as plates, blocks, or linear elements, or they can be utilised as heat-insulating materials or sound-absorbing materials, or even both (Nistorac & Loghin, 2023).

An increasing amount of investigation on the reuse of textile waste has been conducted in the past decade in the field of research. It is a relatively new endeavour, as the first study on the use of textile waste for construction materials was published in 2003. Since 2012, there has been a rise in interest in textile construction materials, and since 2014 a significant amount of experimental data has been released (Rubino et al., 2018). Numerous studies have been published that demonstrate how recycling textile waste materials to make new composites can address the construction industry from three angles: it reduces the environmental impact of construction, enhances some of the fundamental qualities of the composites, and lowers the cost of manufacturing (Nistorac & Loghin, 2023). Textile waste has been recycled for a variety of purposes, such as making low-grade wires, crushing it to make materials that insulate against noise and temperature changes, and using it as a filler or reinforcement for concrete (Pichardo et al., 2017).

Both the scientific community and the building industry are very interested in the fibre- and textile-reinforced mortars. These composite materials can consist of a variety of reinforcement elements, such as long or short fibres, and textiles, including woven and nonwoven fabrics, all enclosed in a cementitious matrix that can take the shape of mortar, cement paste, lime binder, or concrete. Reinforcement is primarily used to fill up cracks and improve the strength, energy absorption ability, and post-cracking behaviour of cementitious composites (Nistorac & Loghin, 2023). Cotton, one of the most widely used natural textile fibres, is the material that goes into making blue denim jeans, the most popular article of apparel in the world. Another method for reusing textile waste is to add 16% staple cotton fibres made from denim waste to a polypropylene matrix. In experimental research, Nistorac & Loghin (2023) performed tensile and fatigue strength tests on the composites that were produced during the injection procedure in order to characterise their morphology. When compared to the pure polypropylene variant, sixty percent better outcomes were achieved. The mechanical behaviour of polymer concrete containing textile residues was investigated. The results showed that the flexural strength of polymer concrete decreases with increasing fibre concentration. However, the flexural strength values were higher than those of cement concrete (Nistorac & Loghin, 2023).

In recent years, researchers in the field of building materials have focused on using solid waste from agricultural goods as pozzolans in the production of blended mortars and concrete. Nowadays, it's common practice to add ashes from burning agricultural solid waste to concrete because of the ashes' pozzolanic action toward lime. The ash produced by burning solid waste from sugar cane is one of the most intriguing materials (Chi, 2012; Yalley & Bentle, 2009). With limited success, numerous initiatives have been undertaken to lower the growing cost of cement manufacture in developing countries. In order to create sustainable material, the construction industry must look for alternatives to traditional virgin material and give careful thought to using agricultural and industrial waste as raw materials to develop innovative construction materials. The organic matter that makes up cow dung includes fibrous material that has passed through the digestive tract of the cow as well as other liquid digestive waste that remains after fermentation, absorption, and filtration, is acidified, and is subsequently reabsorbed. The chemical composition of cow dung is cellulose, lignin, hemicellulose, salts, cells that were shed as the digester passed through the digestive tract, some urea, mucus, and other elements like carbon, nitrogen, hydrogen, oxygen, phosphorus, etc. (Magudeaswaran & Hilal, 2018). According to estimates, a cow generates 10–15 kilograms excrement per day. The cow dung emits methane gas at the rate of 40 litres per kg which accounts for huge emission of greenhouse gas in agrarian-based country like India. According to a recent assessment from the United Nations Environment Programme (UNEP) and the climate and the clean air coalition found that methane emission would be a key in the battle against climate change. Over a 20-year period, methane is 80 times more effective at warming than carbon dioxide, and it causes one million premature deaths annually. Using cow dung for manure or building purpose is an efficient way to convert waste into usable form (Sutar & Patil, 2024).

Most of the existing literature on the use of textile waste in masonry blocks focuses on incorporating it with cement as the binding material. However, studies involving the combination of textile waste with soil for 3D printing or with cow dung as a binder are largely absent. This research bridges that gap by exploring the integration of textile waste with alternative, more sustainable materials. In doing so, it contributes to the development of circular construction practices and promotes innovative approaches to material reuse.

3. MATERIALS AND METHODOLOGY

This research involves exploratory experimental study carried out in two phases. The first phase explores the application of 3D printing technology to produce the construction component using textile residues, river sand, and red soil. Since 3D printing allows for accurate material consumption and waste reduction, it is a sustainable alternative to traditional construction processes. As this is an exploratory research, based on the findings of experiments in the stage one, the variations in the materials and mix design for developing masonry blocks were made and experiments were carried out to achieve lightweight mix design for masonry blocks. The second phase produces new masonry blocks using textile residue, cow dung powder, lime and natural rubber latex (NRL).

3.1 PHASE ONE: 3D PRINTED FABRIC MUD BLOCK

3.1.1 Materials Used in Phase 1

(a) *(b)* *(c)*

Figure 1: Material- (a) initially collected textile waste and shredded cotton fibre; (b) red soil; (c) river sand

Textile Waste

Different types of textile wastes including leftover fabric of stitched cloths, old cloths, etc., were collected initially but due to non-availability of shredding machine the shredded cotton fibres were purchased. Textile waste provides tensile strength and improves thermal insulation properties [See figure-1(a)].

Red Soil

The red soil used for experiment was procured from the nearest plant nursery. As it was rainy season, the soil was wet at the time of collection. Since the experiment required the use of fine coarse-textured soil, it was spread out to dry naturally for 2-3 days. After drying, it was thoroughly sieved to remove large stones, organic matter and other unwanted particles [See figure-1(b)].

River Sand

River sand was bought from one of the nearest construction of the college. It provides bulk to the mud mixture, making the brick larger. Natural sand or river sand constitutes as major fine aggregate in cementitious construction. Especially, masonry block production requires 70–90% sand as raw material (Sundaralingam et al., 2022) [See figure- 1(c)].

3.1.2 Methodology of Experiments in Phase 1:

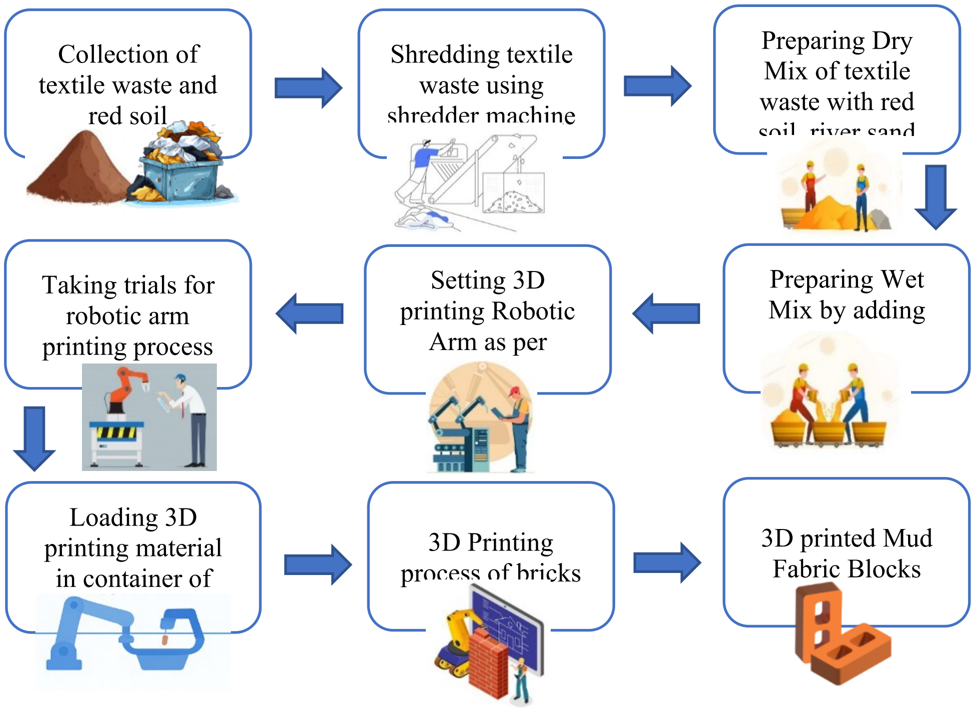


Figure 2: Process of 3D printed fabric mud block

This phase involved developing a mix design for 3D printing of masonry blocks as shown in figure 2. Initially 2-3 experiments were carried out to understand how shredded cotton needs to be used and to get the correct mix design proportions. These experiments were carried out with a household kitchen utensil which can squeeze the material into curvilinear form and had mechanism similar to the 3D printing robotic arm (See figure 3). Table 1 gives the design mix proportions in percentage for the initial experiments carried out with textile waste, red soil and river sand. The first experiment was carried out with mix-1 proportions, but the experiment failed as the cotton fibres were getting stuck through the machine. The failures of experiment 1 was due to long length of cotton strands which got stuck in hole. Taking observations from first experiment, the second experiment used cotton waste that was cut into small pieces of 1-0.5 cm so that the fabric does not get stuck in the machine. And second experiment was carried out by using design mix 2 and it became successful as the cotton waste got blended with mixture which made the mix easily applicable through machine.

(a) (b) (c)

Figure 3: (a) preparing design mix; (b) filling design mix in machine; (c)3d printing block sample

Table 1: Design mix proportion in percentage for initial experiments of 3D printed fabric blocks.

Sr. No.	Material	Mix 1	Mix 2
1	Fabric waste	1	1.9
2	Red soil	90	78.4
3	River sand	9	19.7

After getting the right proportions of the mix, the experiment was carried out using the KUKA KR 30 robot. The design mix proportion consisted of 1.9% fabric waste, 78.4% red soil, and 19.7% river sand. A large design mix was prepared and tested with 3D printing robotic arm (See figure 4). The soil was sun dried to remove the moisture and passed through sieve number 20. The sand too was sun-dried and was passed through sieve number 20. The cotton fabric was cut to smaller lengths and was fibres were separated by hand. The material was weighed and mixed in the dry state. 1.5 litres of water was added to get the desired consistency for 3D printing. The material was mixed thoroughly with hand mixing process. The different types of drawings or scripts were produced to print the mud block with the help of computer aided design software's like rhino and grasshopper. The 3D printing process of the block required 30 minutes to print the block employing KUKA KR 30 robot. The process of experiment is illustrated in figure 4.

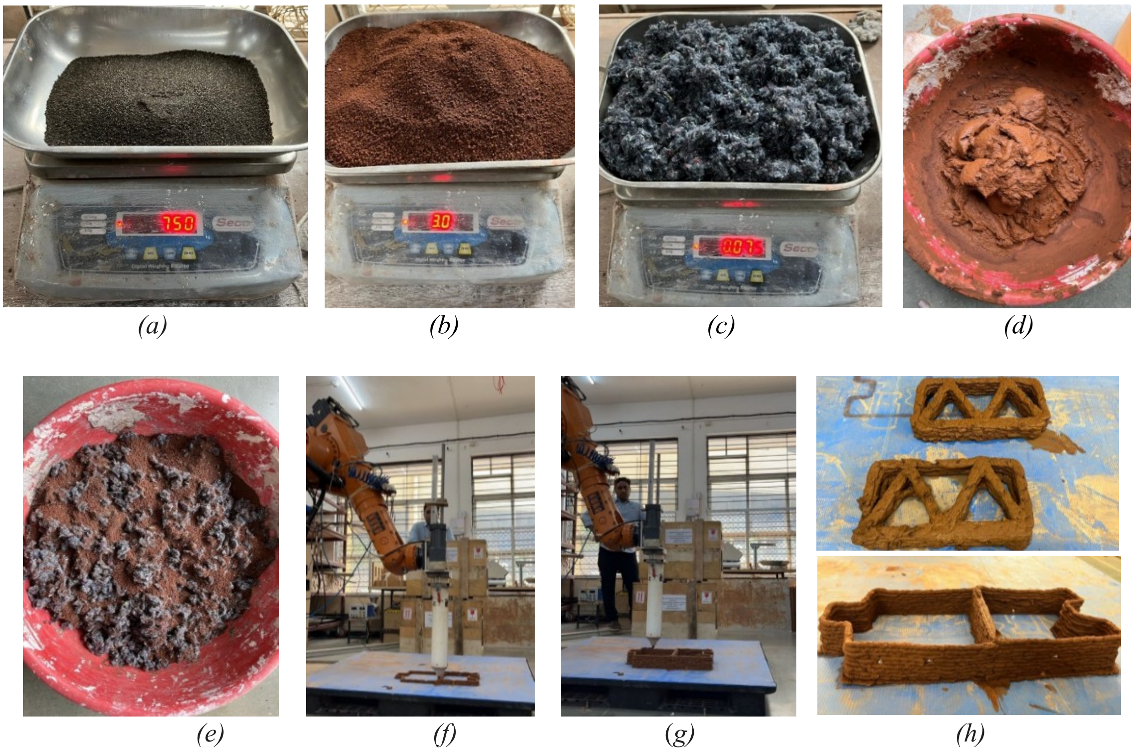


Figure 4: (a) 75 gm of cotton fabric; (b) 3kg red soil; (c) 750 gm of river sand; (d) Dry design mix; (e) Wet design mix; (f) & (g) 3D Printing through KUKA KR 30; (h) 3D printed fabric-mud block

3.1.3. Discussion and Findings of Phase 1 Experiments

After conducting 3D printing experiment using a composite mixture of textile waste, red soil, and river sand, it was concluded that the textile waste is indeed 3D printable along with red soil and suitable for other 3D printing applications like façade design. The material exhibited good consistency; however, there was need to improve the design mix cohesiveness for enhancing the 3D printing quality and mechanical performance.

Since this was an exploratory study aimed at developing a 3D-printable material, the primary focus at this stage was not on testing compressive strength. Instead, the research concentrated on examining the physical properties of the material, such as consistency, surface finish, adhesive behaviour during mixing and printing, as well as the weight and density of the printed blocks. In each experimental phase, only three blocks were produced for initial observation and basic testing. Of these, the first block was tested for compressive strength, the second for water absorption, and the third was retained for assessing surface finish and comparing design mixes.

To understand the compressive strength of material, a hollow block of dimension 300x200x150 mm was casted using a customized deign mould (See Figure 5). This casted block was naturally air-dried, baked at 300-degree temperature for one hour and was kept under shaded area for cooling to enhance its structural integrity. The compressive strength of this baked hollow block was recorded 0.34 N/mm² and the density of the same block was 863 kg/m³. Additionally, a water absorption test was carried out, obtaining a 12.5% result which indicates moderate prosperity.

Further testing involved casting a solid block of dimensions 150x150x150 mm using the same design mix. This block generated a higher compressive strength of approximately 0.91 N/ mm² as it was a solid block (See Figure 6). The density for this solid block was 1396 kg/m³ which was much higher than hollow block. The compressive strength testing of both the blocks was carried out using IS: 3495, Part-I 1992 where the block sample was compressed perpendicularly to the direction of casting. The load was applied without shock and was increased continuously at a constant rate of 14 N/mm²/min until no greater load could be sustained. The water absorption test was carried out using IS: 3495, Part-II 1992 where the sample was immersed in clean water at a temperature of 27 ± 2°C for 24 hours.

The compressive strength of both blocks was much lower than the minimum requirement specified in the IS: 1725, 1982. IS: 1725, 1982 recommends minimum compressive strength of 1.961 N/mm² and 2.942 N/mm² for soil-based blocks used in general building construction for Class 20 and Class 30.

(a) (b) (c) (d)

Figure 5: (a) customized mould design; (b) hollow block casted in mould; (c) block kept for sun drying; (d) compressive strength testing of block

(a) *(b)* *(c)* *(d)*

Figure 6: (a) mould design; (b) solid block casted in mould; (c) block kept for sun drying; (d) compressive strength testing of solid block

3.2 PHASE TWO: FABRIC COW DUNG BLOCKS

3.2.1 Materials Used for Phase 2 Experiments

(a) *(b)*

(c) *(d)* *(e)*

Figure 7: (a) cow dung powder; (b) textile waste; (c) lime powder; (d)Natural Rubber Latex (NRL); (e) Natural Rubber Latex (NRL) mixed with water

Cow Dung

Cow dung powder was used as the basic raw material for making blocks received from Godhan Foundation Pune. Cow dung is wealthy in minerals like Potassium, Magnesium, Sodium and Manganese and is created from natural matters. Cow dung improves workability and mould ability of mixture [See figure- 7(a)].

Textile Waste

Different types of textile wastes including leftover fabric of stitched cloths, old cloths, etc., were collected initially but due to non-availability of shredding machine the shredded cotton fibres were purchased. Textile waste provides tensile strength and improves thermal insulation properties [See figure- 7(b)].

Lime

Lime was ordered from the chemical company in Pimpri Chinchwad Pune. It is a calcium-containing inorganic mineral composed on the whole of oxides, and hydroxide, commonly calcium oxide or calcium hydroxide. Lime acts as a stabilizer to strengthen the block. It also reduces shrinkage and cracking during drying [See figure- 7(c)].

Natural Rubber Latex

It was ordered from the chemical company located at Delhi. Natural Rubber Latex (NRL) is an agricultural-based natural polymer. Natural rubber latex (NRL) is an agricultural-based natural polymer extracted directly from heveabrasiliensis (rubber tree). India being the sixth-largest producer of rubber worldwide, availability of NRL can be relied upon for making soil–cement blocks. Beneficial properties of NRL which supports soil stabilization are, miscibility with water before coagulation of latex, immiscibility after coagulation, elastomeric property, non-toxicity, compatibility with various soils and high melting point (180 °C) (Jose & Kasthurba, 2021) [See figure- 7(d)].

3.2.2 Methodology of Experiments in Phase 2:

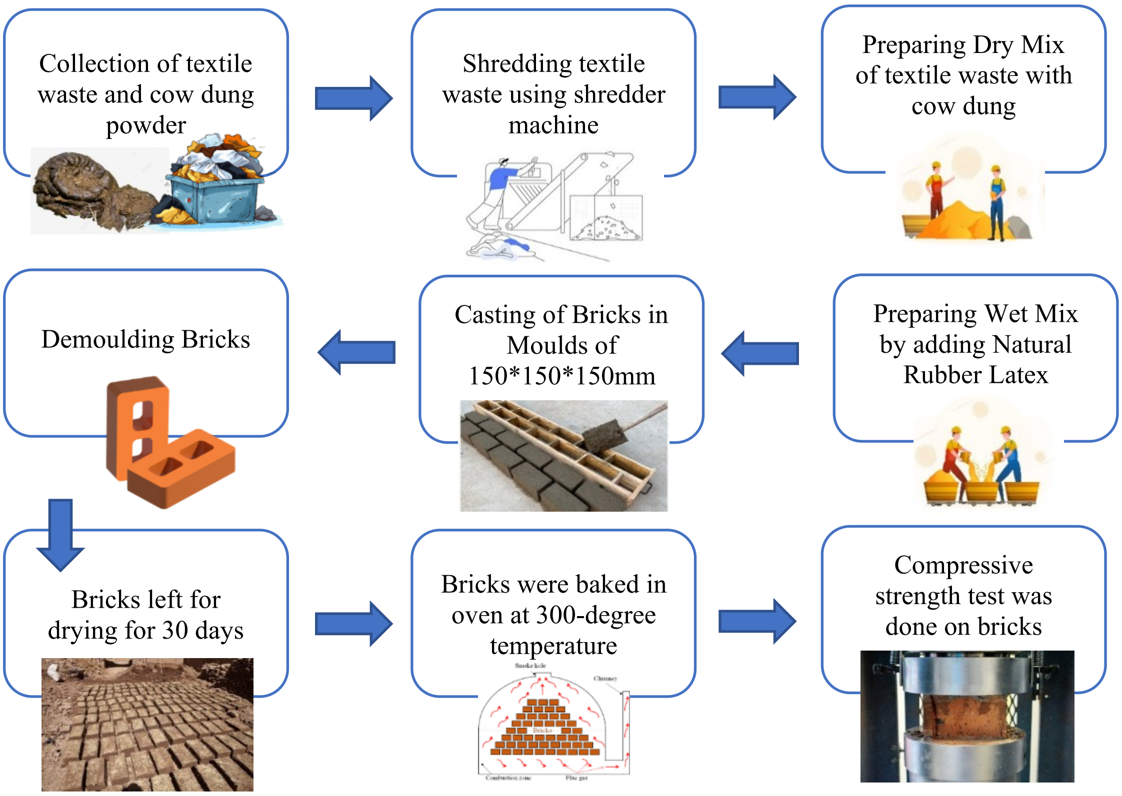


Figure 8: Process of manufacturing cow-dung fabric mud block

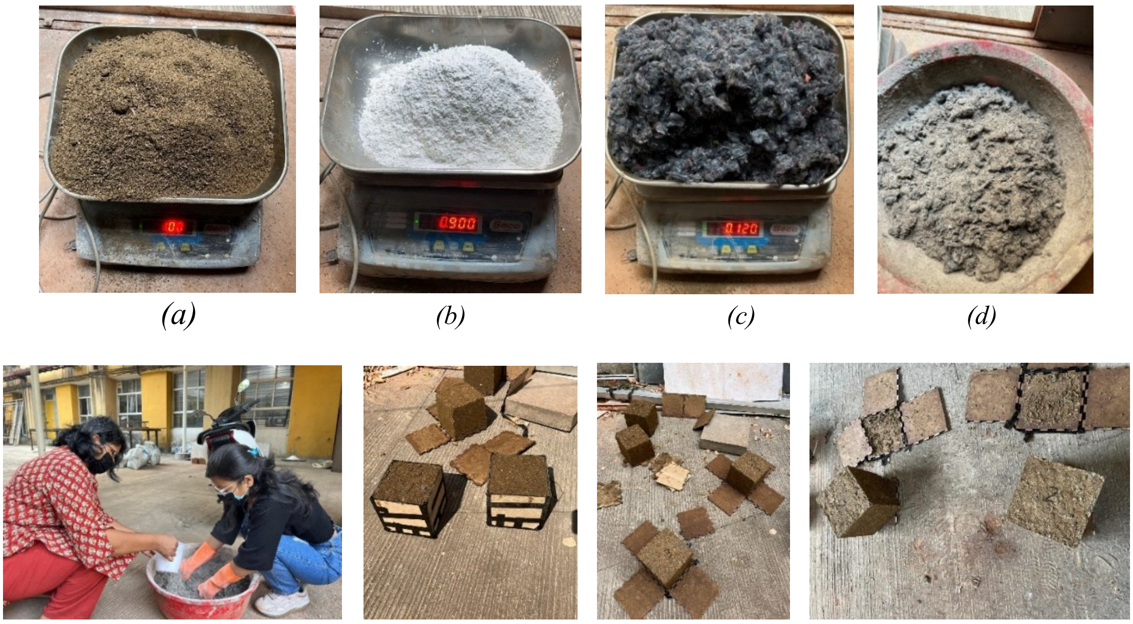
To address limitations identified after 3D printing experiment – specifically the low compressive strength and the excessive weight of the masonry block, a new design mix was developed along with some new materials. The primary objective was to achieve the lightweight masonry block and achieve the compressive strength in accordance with the IS codes specifications.

To improve the blocks mechanical properties, particularly compressive strength, there was need to use the natural adhesive. In the modified design mix, red soil was replaced by cow dung to reduce the weight of the block, and the river sand was replaced by the lime, to reduce the weight, improve the bonding without compromising the compressive strength of the block. Furthermore, the Natural Rubber Latex was used as a biodegradable natural adhesive to improve the bonding of materials and strength of the composite material. In this phase, the experiment involved various steps as illustrated in Figure 8. Including collection of materials to casting blocks to conducting the tests to check the compressive strength of the blocks.

The process of manufacturing cow dung blocks from cow dung dry powder and textile waste involved preparation of design mix, molding, sun drying and baking of blocks. The dry design mix of cow dung powder, textile waste fibers, and lime powder was prepared and was mixed thoroughly for 10-15 min through hands. The NRL mixed was then mixed with five liters of water to the dry mix to get the required constancy of the material to cast the blocks. The blocks were casted into 150x150x150 mm size of the molds. The blocks were kept for drying around 30 days and were baked in oven at 300-degree temperature for 30 min. Table 2 indicates the new design mix proportions in percentage of cow dung, lime, textile waste fabric and natural rubber latex, the density of the blocks and their compressive strengths. Within the three design mixes prepared for the experimentation, the percentage of textile fabric waste and natural rubber latex which acts as binder were kept constant and the proportion of cow dung to lime changed in each mix by weight to evaluate the impact of cow dung on the density of the blocks and the compressive strength.

Table 2: Design mix proportion in percentage for cow dung fabric blocks.

Sr. No.	Material	Mix 1	Mix 2	Mix 3
1	Cow dung	56	61	66
2	Lime	30	25	20
3	Fabric	4	4	4
4	Latex	10	10	10



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 9: preparing design mix as per proportions: (a) cow- dung powder; (b)lime powder; (c) textile waste; (d) dry mix: (e) Adding NRL to dry mix; (f) casted cow-dung fabric block; (g) demoulding blocks; (h) drying blocks under sunlight for 30 days

3.2.3 Discussion and Findings of Experiments in Phase 2

The second phase of experimental research focused on using a modified design mix containing cow-dung, fabric waste, lime, and natural rubber latex, to develop a lightweight sustainable masonry block. The results confirmed that the textile waste, particularly shredded cotton can be combined with cow dung to produce masonry bocks.

Three design mixes mentioned in Table 2., were tested, each mix produced a solid block of dimensions 150x150x150 mm. A significant observation was noted across all three mixes that there was substantial weight reduction in blocks, with the blocks weighing 1.6 kg, 1.6 kg and 1.4 kg respectively. This reduction in weight of block reflected a decrease in material density compared to the first red soil masonry solid blocks.

However, the compressive strength tests achieved by these mixes were 0.23 N/ mm^2, 0.31 N/ mm^2 and 0.17 N/ mm^2 respectively as indicated in Table 3. The compressive strength testing of the blocks was carried out using IS: 3495, Part-I 1992 where the block sample was compressed perpendicularly to the direction of casting. The load was applied without shock and was increased continuously at a constant rate of 14 N/mm^2/min until no greater load could be sustained. These low compressive strength values were below the minimum requirement of the IS: 1725, 1982 for the soil-based blocks. Hence, it was concluded that the complete replacement of red soil is not feasible for achieving the mechanical and structural integrity of the blocks.

Additionally, due to the use of cow dung powder, fungal growth on the surfaces of each block was observed on all three masonry blocks. Mix 2 exhibited the highest fungal growth due to prolonged wet surface exposure, followed by Mix 1. Mix 3 showed minimal presence of fungus. This outcome highlighted that there is need for pre-treatment of cow dung powder to improve the durability, minimize hydrophilic properties and improve the surface finish of the product. Fungal growth may be attributed to the weather conditions as the experiments were conducted in rainy seasons and the blocks took a longer duration for drying.

Table 3: Test results for cow dung fabric blocks.

Sr. No.	Description	Age	Block size in mm (lxbxh)	Weight (kg)	Density (kg/m3)	Load (kN)	Compressive strength (N/mm²)
1	Mix 1	30 days	150x143x150	1.69	514.29	5.0	0.23
2	Mix 2	30 days	150x148x150	1.60	502.84	6.9	0.31
3	Mix 3	30 days	150x142x148	1.45	455.61	3.6	0.17

4. CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

The first phase of this experimental research aimed to develop an innovative method for utilizing textile waste as a raw material for 3D printing mud blocks. The experiment confirmed that textile waste, particularly shredded cotton is compatible with red soil and river sand for 3D printing applications. The designed mixture demonstrated acceptable consistency; however, further improvement in the cohesiveness of the mix was required. One significant finding was that the textile waste, when shredded into small pieces of size between 5 mm to 10mm, resulted in a more uniform mixture. This research was successfully executed and represented a promising innovation that not only addresses the environmental impacts of conventional construction but also offers a solution to the textile industry’s waste management challenges. As with all experimental research, challenges were encountered and had to be addressed. These included achieving the right consistency of the mix, ensuring the quality and uniform size of the recycled fabric fibres, and working within the limitations of the 3D printer's barrel, which had a capacity of only 3 kg. These constraints made it necessary to print a single block in two parts, thereby complicating the testing of compressive strength. Recognizing and responding to these limitations was essential for the effective execution of the research.

In the second phase of the research, an attempt was made to reduce the weight of the blocks by replacing red soil with cow dung powder and sand with lime. The cow dung formed a bond with the textile fibres when combined with lime and latex as natural binders. However, the compressive strength achieved in both phases of the experiment did not meet the standards specified in the IS code 1725, 1982 specification for soil-based blocks used in general building construction. Another major challenge in assessing the applicability of these non-conventional materials is the absence of an Indian Standard Code for sun-dried cow dung blocks. With the growing emphasis on circular construction practices aimed at reducing resource consumption, there is a clear need to develop Indian Standard Codes for alternative building materials. In both experimental phases, it became evident that micro-mixing of materials cannot be achieved through manual mixing. A mechanized mixing process is therefore essential to ensure the uniform dispersion and bonding of materials, which would improve both the mechanical performance and biological stability of the blocks.

To address the key challenges identified such as low compressive strength, excessive weight in earlier blocks, and fungal growth due to cow dung powder, a revised approach will be adopted for future research. The next phase of the research involves combining red soil with fresh cow dung and eliminating the use of cow dung powder entirely. This modification is expected to enhance the bonding characteristics, mechanical strength, and overall durability of the 3D-printed blocks. This research contributes towards the development of construction materials using industrial waste enhancing circularity in the construction industry minimizing resource consumption and depletion.

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