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MICROBE INDUCED CALCIUM CARBONATE PRECIPITATION MEDIATED BRICK MANUFACTURING

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1.0 GENERAL BACKGROUND

South Asia is home to nearly a quarter of total global brick production. Indian brick kiln industry is the second largest brick producer in the world, next to China, having more than 100,000 operating units and producing about 250 billion bricks annually. It employs about 10 million workers and consumes about 25 million tons of coal annually (Maithel, Sameer et al., 2012). Brick kilns, involving the burning of low-grade coal, are one of the major sectors that contribute to air pollution in South Asia. The brick sector is responsible for up to 91 % of total Particulate Matter (PM) emissions in some South Asian cities. The estimated emission from brick kiln production in India is about 0.94 million tonnes of PM; 3.9 million tonnes of carbon monoxide (CO) and 127 million tonnes of carbon dioxide (CO_2) per year (Uma Rajarathnam et al., 2014).

Asia produces approximately 1.2 trillion bricks per year. The global brick industry is a major source of CO_2 emissions. This does not include any of the other inputs used during the brick production process or the diesel required to transport the bricks. Just from the coal consumed, the brick industry in the top five Asian brick-producing countries emits 1.2% of total global anthropogenic CO_2 emissions (Lopez et al., 2012). Brick kilns are significant emitters of black carbon and is known to contribute to climate change and local health problems. Black carbon and Suspended Particulate Matter (SPM) are the second-largest contributors to global warming after CO_2. More than 2.4 million premature deaths can be attributed to black carbon every year.

Buildings plays a huge role since human civilization. It acts as a place of shelter, a place to work and communicate, and also a place to organize a where dedicated things are in a community. As human civilization continues to improve and change, so does the buildings that are constructed. Different ways are explored to build a structure, from the perspective of physics, visual aesthetics, unique purposes, and also the materials.

The health of the climate is getting worse day by day all due to air pollutants, especially black carbon. The greenhouse gases (GHG) such as carbon dioxide, ozone, methane, water vapour, and nitrous oxide have a tendency to captivate and release radiations in the thermal infrared range, causing the greenhouse effect and a primary reason for global warming. Global warming is increasing rapidly and the fourth biggest carbon emitter in the world is India. GHGs are the major pollutant in the environment and the construction industry is considered 19% responsible for it. But especially in a developing country like

India, infrastructure is a basic need. Around 40% of the carbon footprint is generated by construction and buildings together due to various processes like lighting, cooling, and heating of building materials. The issue of increasing carbon footprint is not related to one country but it is a global issue and a conference was held in Glasgow. India presented its “panchamrit” to achieve five major climate targets in the conference. It includes achieving the target of net zero emissions by 2070. Up to 2030, India wants to fulfil its 50% energy requirements from renewable energy. Up to 1 billion tons of total projected carbon emissions should be reduced by 2030, 45% reduction of carbon intensity by 2030 over 2005 levels and to reach the target by 2030 of 500 GW of non-fossil energy capacity. In any construction project, there are two types of CO_2 emissions that are direct (operational) and indirect (embodied). The direct CO_2 emissions are usually generated from the consumption of energy at the site and during other various construction activities, while indirect carbon emissions are generated through the extraction of construction materials, production, transportation, demolition, and other non-building activities. Both are equally harmful to the environment. Processes such as extraction of raw material, manufacturing installation, and demolition lead to climatic degradation

Emission of huge quantity of toxic elements from brick kilns is causing serious health hazards. The brick kilns emit toxic fumes containing suspended particulate matters rich in carbon particles and high concentration of carbon monoxides and oxides of sulphur (SO_x) that are harmful to eye, lungs and throat. These air pollutants stunt the mental and physical growth of children. According to the data, the primary source of SO_x, the major pollutants in the air is traffic vehicles (55.8%), followed by brick manufacturing industry (28.8%). And the primary source of NO_x (nitrogen oxides) pollutants is also traffic vehicle (54.5%) and brick manufacturing industry (8.8%). Also, nearly 25 to 26 percent of the country’s wood production are used for burning bricks every year, causing deforestation. Bricks are made for building. But the country’s brick kilns are churning out the basic ingredients for construction in a way that is doing more harm than good (Deepasree M Vijay et al., 2011).

1.1 MICROBE INDUCED CALCIUM CARBONATE PRECIPITATION

The manufacturing of conventional building materials including cement, lime, and timber produce large amount of carbon dioxide. Thus, the development of green and sustainable construction building materials have attracted wide attention from civil engineers. Bio-consolidation of construction materials, a new method of consolidation, has been introduced recently..

MICP is the most common bio-consolidation process that has been widely reported in recent years. In the MICP process, urea is hydrolysed by microbial urease to form ammonium and carbonate ion. The produced carbonate ions react with calcium ions to precipitate as calcium carbonate. The calcium carbonate precipitation can function as cementation materials to bond geomaterials together.

1.1.1 PROCESS OF MICP

By hydrolysing 1 mol urea, 1 mol ammonia (NH_3) and 1 mol of carbamic acid (NH_2COOH) is produced. Carbamic acid reacts with water producing 1 mol of bicarbonate along with 2 moles of ammonia. Bicarbonate again is reduced to carbonate ion and H^+ ion. Ammonia reduces to ammonium ion and OH^-. An increment in H^+ and OH^- ions cause increase in pH. The cell wall of bacteria is negatively charged. Thus, bacterial cell wall attracted Ca^{2+} ions and react with CO_3^{2-} ions to form calcium carbonate ($CaCO_3$) precipitation. The general chemical equation for MICP is as follows:

$Ca^{2+} + 2HCO_3 + H^+ \rightarrow CaCO_3 + CO_2 + H_2O$

This reaction shows how calcium ions (Ca^{2+}) and bicarbonate ions (HCO_3^-) combine in the presence of acidic conditions (H^+) to form calcium carbonate ($CaCO_3$), carbon dioxide (CO_2) and water (H_2O).

However, the specific equation may vary depending on the type of microbe and the conditions that cause precipitation, for example, some microbes may produce urease enzymes that hydrolyse urea into ammonia (NH_3) and carbon dioxide (CO_2) that can then react with calcium ions to form calcium carbonate. The equation for this process would be:

$Ca^{2+} + 2NH_3 + 2CO_2 + H2O \rightarrow CaCO_3 + 2NH_4^+$

Overall, MICP is a complex process that involves various chemical reactions and microbial activities

2 SCOPE

- MICP mediated brick manufacturing helps to eliminate the carbon footprint caused by brick kilns and cement manufacturing, related to cement blocks.
- Low carbon emitting brick manufacturing process helps to lead in the direction of sustainable development, especially for countries that have high population density.
- It is a cost effective and economic way of brick manufacturing when manufactured in large scale.
- It provides an alternative method for manufacturing high class bricks.

3 OBJECTIVES

- To develop a brick manufacturing process that can reduce carbon footprint.
- Determine the effectiveness of different base materials in manufacturing.
- Determine the effectiveness of $CaCO_3$ precipitation using bacterial strain (*Bacillus Subtilis*).
- Investigating the effectiveness of eco-friendly reinforcements in increasing the strength of the brick.
- Determining the strength and ascertaining quality of manufactured bricks by conducting compression test, water absorption and efflorescence test.
- To conduct characterisation study of manufactured bio-brick.

4 SOCIAL RELEVANCE

- Alternative and cleaner form of brick manufacturing than all the existing forms of manufacturing.
- Reducing the dependability of fossil fuels in brick manufacturing process.
- Employing the use of natural and locally available fibres and industrial waste to attain strength parameters of regular brick.
- Currently, the world is struggling to fight climate change. Thus, more eco-friendly forms of manufacturing process for construction material are needed. In this regard, MICP can be a better alternative.

5 METHODOLOGY

This chapter mainly discuss the methodology of the MICP mediated brick manufacturing process and preparation of the cementation solution. It also discusses the importance of bacteria and the working principle of Microbe Induced Calcium Carbonate Precipitation. It also explains the specifications of mould used in bioreactor.

5.1 CEMENTATION MEDIA

Cementation media was used to induce the calcium carbonate precipitations during the MICP process. The chemicals used for the study has been obtained from Chemind, Thrissur, Kerala. The concentration of chemicals in cementation medium is as follows.

Table 3.1: Chemical composition of cementation media (Yang Li et al., 2020)

Chemicals	**Concentration**
Urea	30 g/L
$CaCl_2.H_20$	73.6 g/L
NH_4Cl	10 g/L
$NaHCO_3$	2.12 g/L
Nutrient broth	3 g/L

A high pH value in combination with high calcium concentration is the optimal basis for $CaCO_3$ precipitation. The bacteria precipitate in the basic medium than in an acidic and neutral medium (Poornima V. et al., 2021). The pH of the prepared sample was tested using pH meter and litmus paper to determine the nature of the cementation media.

Fig 3.2: Testing the pH of cementation media using litmus paper

The obtained pH of cementation media was around 8, that is alkaline and hence a satisfactory result for MICP.

Bacillus subtilis was the bacterial solutions used in this study. *B. subtilis* was chosen since it is a non-pathogenic bacterium. It is found in soil and human intestine, hence can be obtained or isolated easily. The cell concentration of *B. subtilis* used is between 10^3 and 10^8 cells/ml and it has been obtained from Microbiology Department, Kerala Agriculture University, Mannuthy.

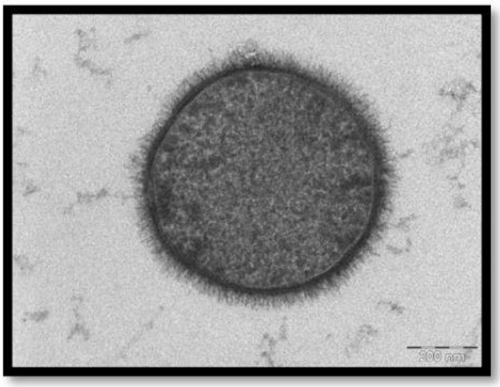


Fig 3.3: TEM micrograph of *B. subtilis* cell in cross-section

The bacteria produce urease enzymes, that can hydrolyse urea to form ammonium ions and carbonate ions. These carbonate ions can then react with calcium ions in the environment to form calcium carbonate crystals. In addition, *B. subtilis* can also alter the pH of the environment, creating conditions that are more conducive to calcium carbonate precipitation. By producing alkaline compounds, such as ammonia, the bacteria can increase the pH of the surrounding environment, promoting the formation of calcium carbonate. An enzyme urease is produced by metabolic activities under certain environmental conditions. It is then hydrolysed into carbamate and ammonia. It subsequently forms ammonia and carbonic acid that form into bicarbonate, ammonium, and hydroxide ions. The reactions take place in the mould are as follows:

$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3$

$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$

$H_2CO_3 \rightarrow HCO^{3-} + H + 2NH_3 + 2H_2O \rightarrow 2NH_4 + 2OH^-$

These two reactions give rise to a pH increase. Because of this, the bicarbonate equilibrium shifts, and resulting in the formation of carbonate ions. As a result, the carbonate and calcium ions form $CaCO_3$.

$HCO^{3-} + H + 2NH_4 + 2OH^- \rightarrow CO^{3-}{}_2 + 2NH_4 + 2H_2O$

$CO_3^{-2} + Ca^{2+} \rightarrow CaCO_3$

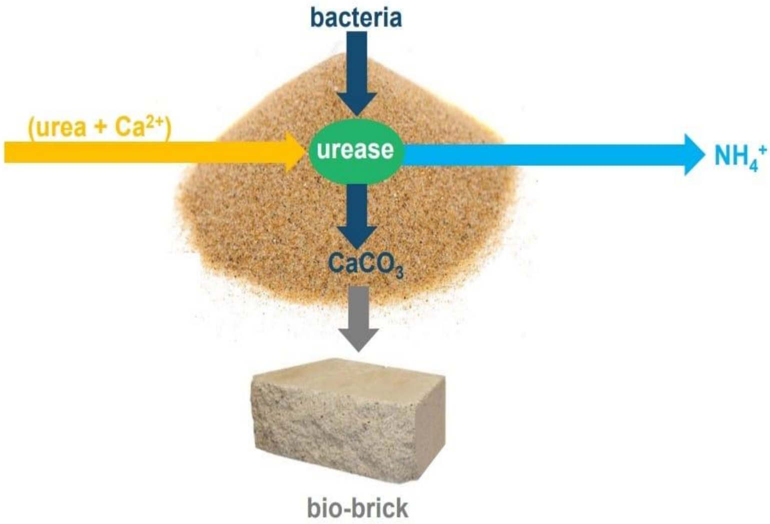


Fig 3.4: Schematic representation of bio-brick

5.3 MATERIALS

Aggregate is a building and construction material that combines with binding agents to create necessary compounds. The aggregate guarantees consistency and volume in the finished product, as well as resistance to wear and erosion and other physical properties.

5.3.1 STEEL SLAG

The steel slag used for this study was obtained in the form of huge stones from Creations Cast Factory, Athani, Peringandoor, Thrissur, Kerala. It has been washed thoroughly and crushed it manually. After that, the crushed steel slag was sieved through different IS sieves. The majority portion passed through 2.36 mm IS sieve. Thus, the best possible practical size of steel slag was less than 2.36 mm and this size of steel slag was chosen for manufacturing bio- bricks.

5.3.2 CLAY

The clay was collected from Fathima Tile Factory, Ollur, Thrissur. It contains moisture in its raw form, thus allowed it for the sun drying process. Then it was powdered and sieved to obtain the standard size of clay, 0.002 mm.

5.3.3 COIR

Coir fibres offer a sustainable and environmentally friendly alternative to traditional reinforcement materials in construction applications. Processed coir was purchased directly from the market.

5.3.4 JUTE

The jute fibres used in the manufacturing of bio-brick were purchased from the market. Prior to use, the jute fibres were washed thoroughly using a sieve and deionised water, followed by autoclaving at 121^0C for 20 minutes. The fibres were then oven dried at 50^0C.

5.4 BATCH REACTOR SET UP

The batch reactor was set up in a plastic tub. The specially prepared mould that can manufacture 3 bricks at a time was partially immersed into the cementation media in the tub. The porous walls of mould facilitate the cementation media to enter into the brick. An air pump of flow rate 0.5 L/min was provided to trigger MICP process. A unit surcharge load is provided on the top of bricks that helps in binding the aggregate. The concentration of cementation media is as mentioned in section 3.2.

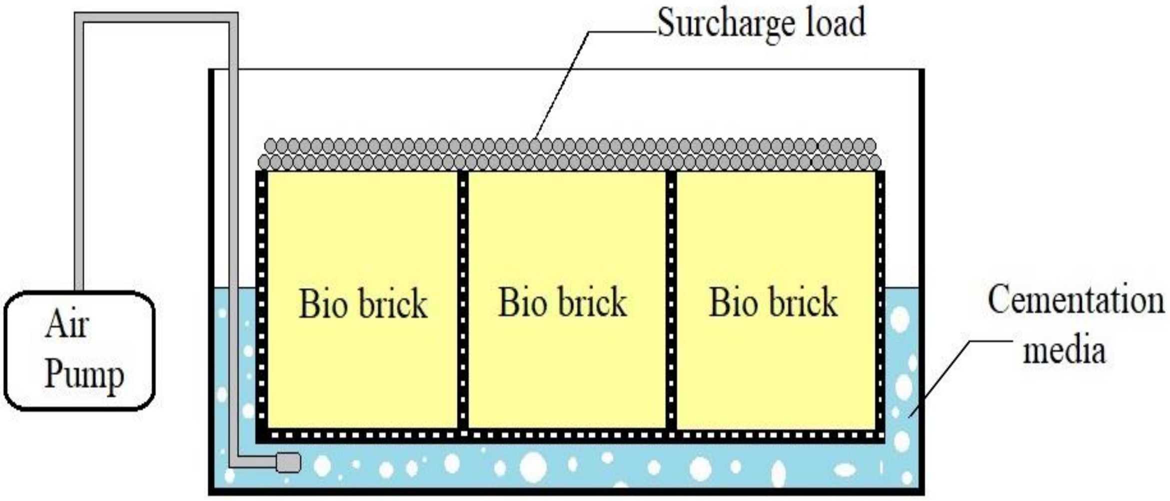


Fig 3.5: Schematic drawing of batch reactor set up model

The mould was designed in such a way that, it facilitates the cementation media to enter into the bricks, thereby helping to precipitate calcium carbonate. Each mould consists of 3 chambers that can mould 3 bio-bricks at a time. The size of each chamber is same as the size of a normal brick as per IS specification, i.e., 190mm × 90mm ×90mm.

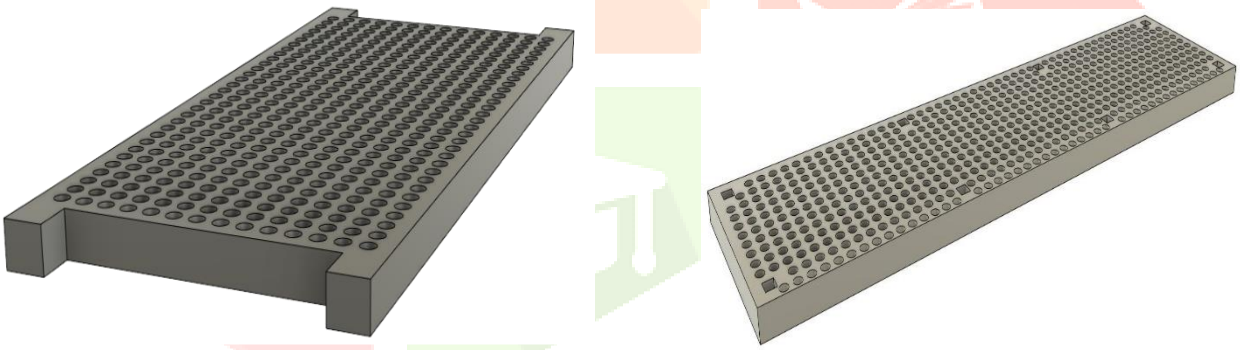
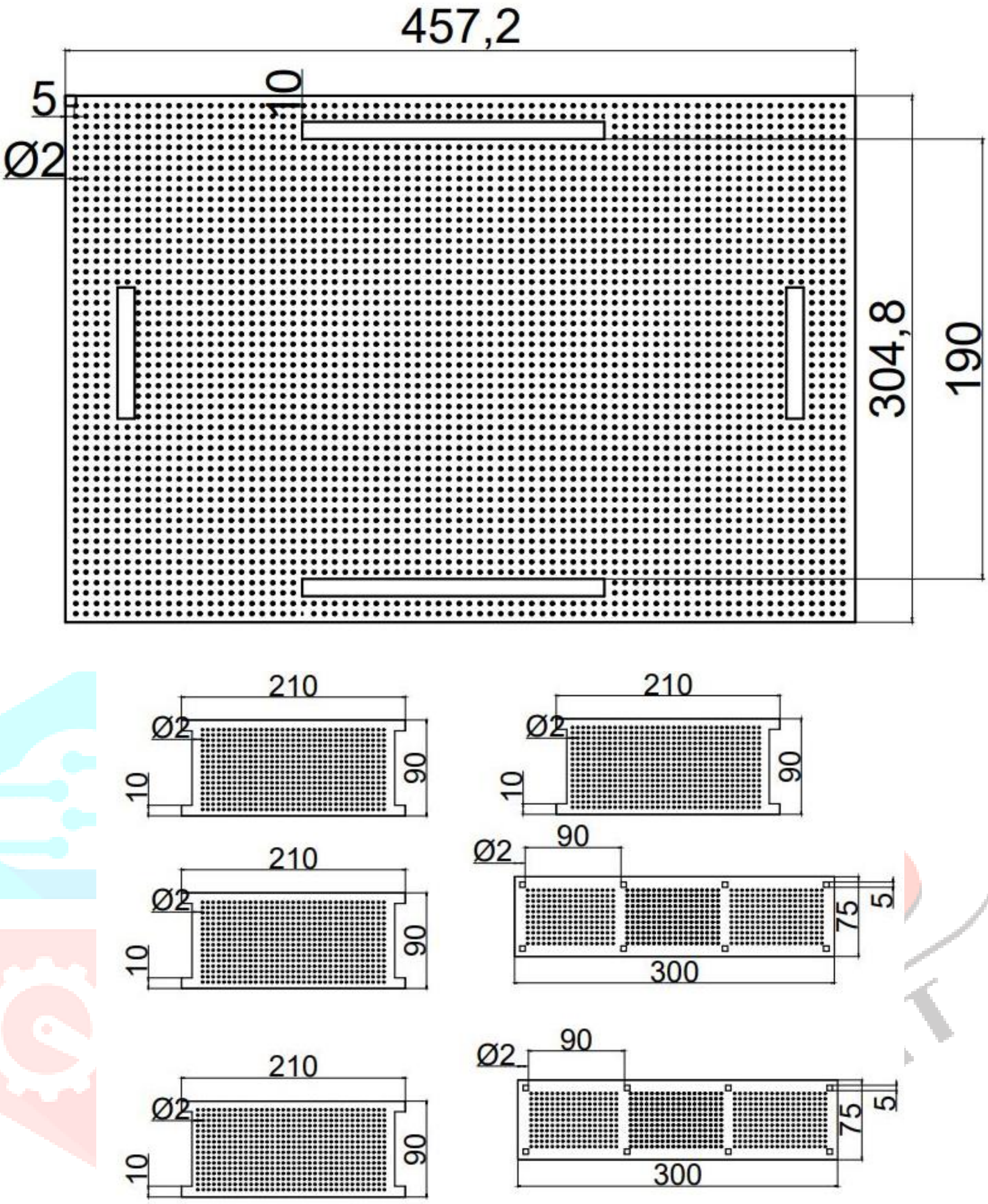


Fig 3.6: 3D drawing of side pieces of mould



All dimensions in mm

Fig 3.7: 2D drawing of mould

The muti wood sheet was bought and cut into pieces. The perforations were made using Computerised Numerical Control (CNC) machine at Fourth Axis CNC Solutions, Thrissur. The 2D drawing of the mould was designed using AUTOCAD 2022 Software and 3D drawing using Autodesk 3D Fusion. The mould was built in such a way that it can be demoulded and fitted as per the convenience as shown in Figure 3.11 and 3.12 respectively.

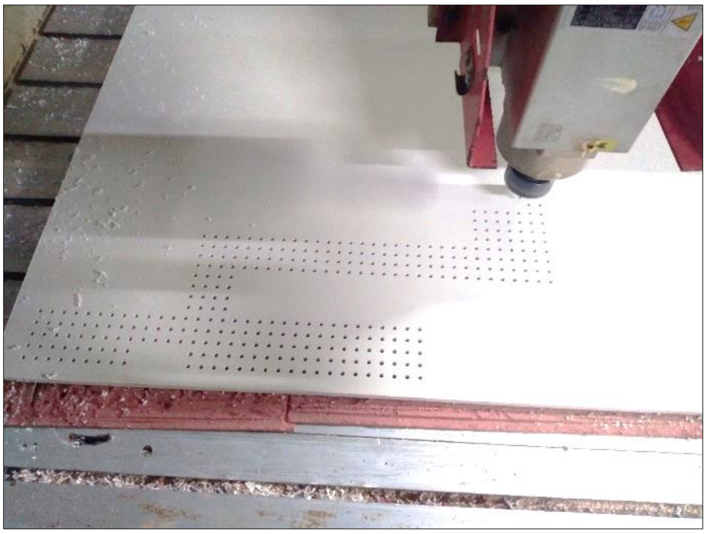
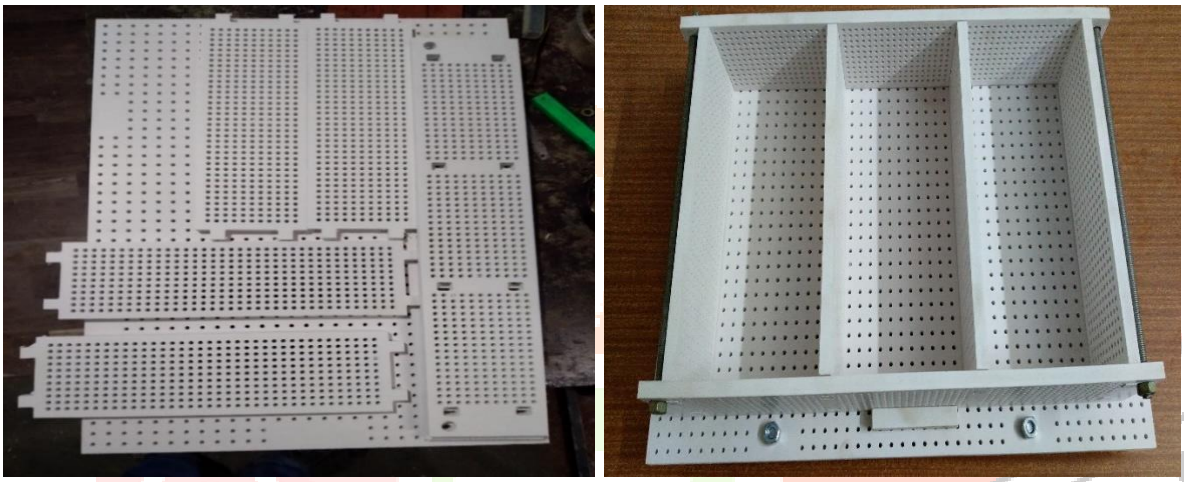


Fig 3.8: CNC cutting



(a) (b)

Fig 3.9: Mould prototype (a) Demoulded (b) Fitted

6 PRELIMINARY INVESTIGATIONS

This chapter covers the preliminary studies involving the base materials, bacteria. It also covers the various physical characters of base materials including specific gravity, water holding capacity. It also explains the effect of Calcium Carbonate precipitation by the changing the bacterial concentration in cementing solution.

6.1 DETERMINATION OF OPTIMUM BACTERIAL CONCENTRATION

An experimental study was conducted based on the different bacterial concentrations. The experiment carried out in six beakers (each 200 ml) under normal lab conditions. Each beaker contains *Bacillus subtilis* and the cementing solution consists of calcium chloride, urea, ammonium chloride and sodium bicarbonate and nutrient broth, in proportionate to the concentration mentioned in section 3.2. The conical flasks contain different bacterial cell concentrations such as 10^3, 10^4, 10^5, 10^6, 10^7 and 10^8 cells/ml. The conical flasks were allowed to set for 7 days to assess the precipitation.

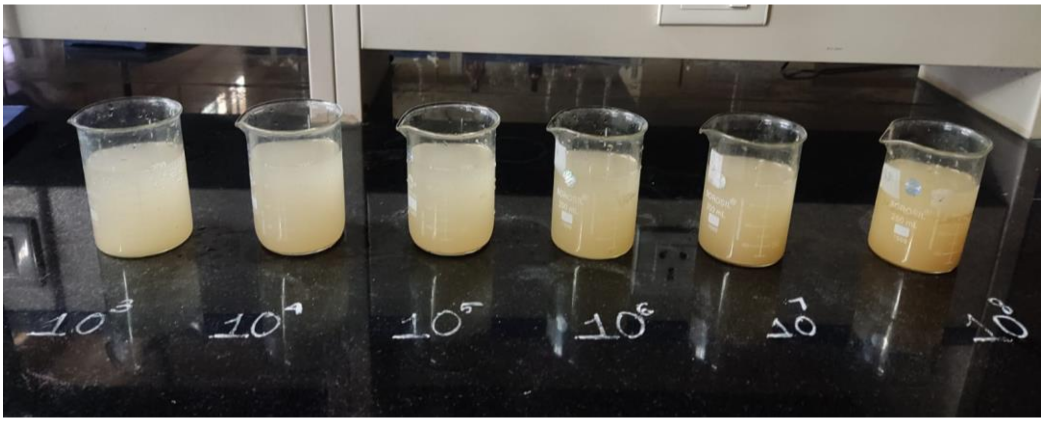


Fig 4.1: Cementing solution kept in beakers containing different bacterial cell concentrations

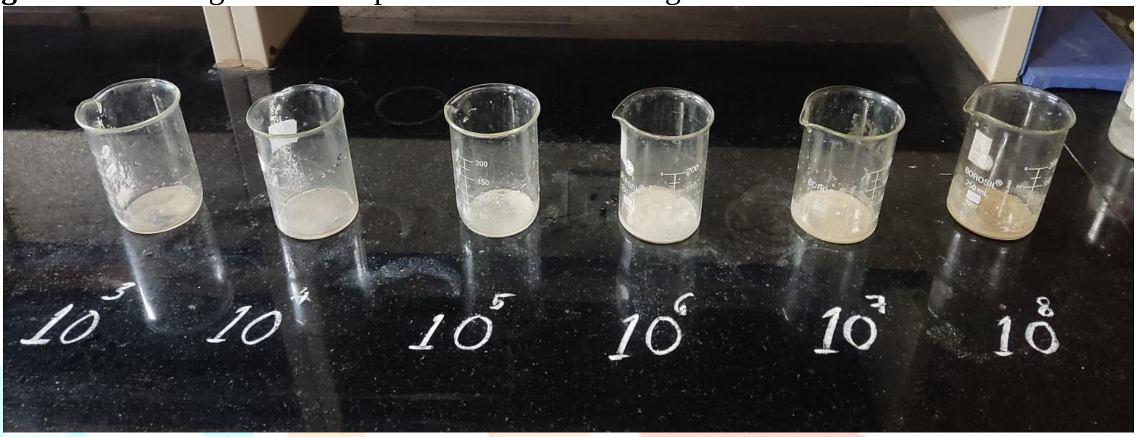


Fig 4.2: Precipitation of Calcium carbonate in beakers after 7 days

Table 4.1: Observation table Precipitation of Calcium carbonate in beakers after 7 days

Bacterial concentration	**Weight of the beaker with precipitation (In gm)**	**Weight of precipitation (in gm)**
10^3	98.60	2.15
10^4	99.15	2.70
10^5	101.40	4.95
10^6	105.73	9.28
10^7	103.32	6.87
10^8	102.70	6.25

Sample calculation
For bacterial concentration 10^3cells/ml;
Weight of the beaker = 96.45 gm
Weight of the beaker with precipitation = 98.60 gm
Weight of the precipitation = 98.60 – 96.45 = 2.15 gm
Maximum precipitation was obtained at bacterial concentration of 10^6 cells/ml. Thus, it was chosen for further studies.

6.2 SPECIFIC GRAVITY OF BASE AGGREGATES

Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. The test was conducted using pycnometer, to understand the phase relationship of air, water, and solids in a given volume of the soil. The weight of the empty clean and dry pycnometer (W_1) as well as the weight of pycnometer with dry aggregate (W_2) is recorded. The pycnometer was filled with water along with aggregates and allowed to settle (W_3). The pycnometer was emptied and fill with water only till the mark (W_4).

Specific gravity of the sample was calculated using the following equation:

$$\text{Specific gravity, } G_s = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)}$$

Table 4.2: Specific gravity test results

Sample No.	Sample 1	Sample 1
Weight of the empty clean and dry pycnometer (W_1)	390 g	390 g
Weight of pycnometer with dry aggregate (W_2)	590 g	630 g
Weight of pycnometer with water and dry aggregate (W_3)	1175.65 g	1200 g
Weight of pycnometer with water (W_4)	1050 g	1050 g
Specific gravity, G_s	2.69	2.67

Fig 4.3: Specific gravity testing

The specific gravity of the aggregate is **2.68**.

6.3 WATER HOLDING CAPACITY OF BASE AGGREGATES

Determining water holding capacity of aggregates is an important test in civil engineering investigation. Oven dried samples (clay and steel slag in equal proportion) are allowed to saturate for 24 hours. A funnel placed on the top of a measuring cylinder was used for the test. A certain amount of aggregates were taken in the funnel and a particular amount of water was poured to it. The amount of water collected in the measuring cylinder was noted.

$$\text{Water holding capacity} = \frac{\text{Volume of water retained}}{\text{Weight of aggregate}} \times 100$$

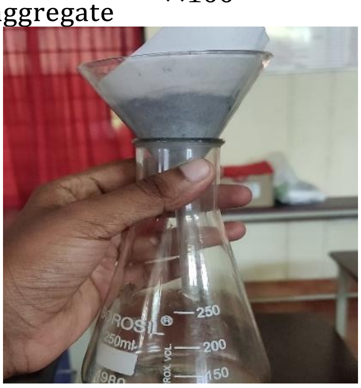


Fig 4.4: Water holding capacity testing

Table 4.3: Water holding capacity test results

Sample	Sample 1	Sample 2
Weight of aggregate (X)	50 g	50 g
Volume of water poured (Y)	50 ml	50 ml
Volume of water collected in measuring jar (Z)	35 ml	34 ml
Volume of water retained (Y-Z)	15 ml	16 ml
Water holding capacity of aggregate	30 %	32 %

Water holding capacity of aggregate = Average of two results
= **31%**
One brick contains 3000 g of base aggregate.
Therefore, one brick can hold 31% of 3000 g, i.e., 930 ml of water.
Thus 800 ml of bacteria was added to each bio-brick, so that osmosis would takes place in such a direction that cementation media would enter into the bricks and helps in MICP.

7 EXPERIMENTAL INVESTIGATIONS

This chapter also covers the experimental investigation of the bio-bricks of different combinations of reinforcements. It also covers the execution of construction of bioreactors for manufacturing of bio-bricks. It also explains the role of different components of bioreactors in efficient MICP process.
The first trial run was conducted using following combinations.
(1) steel slag + coir
(2) clay + coir
(3) clay + steel slag + coir

It is kept for manufacturing into bricks in brick mould, with bacterial cell concentration 10^6 cells/ml. The walls of the mould were covered with filter paper, so that aggregates don't penetrate through the holes in the mould and at the same time, it won't restrict the cementing solution to enter into the mould.

Fig 5.1: Raw materials- Clay, steel slag and coir

The brick mould is immersed in a cementing solution up to the brim of mould. An additional aeration is provided through air pump that will help in MICP process. The base aggregates were placed in three layers with 20-25 compaction given for each layer. Reinforcements were also arranged in layered in between each layer. The brick is kept fully immersed in cementing solution for 7 days and then demoulded.

7.1 MATERIALS USED

Materials used in third execution is shown in figure 5.4

Table 5.2: Materials used in Execution 3

Sl.NO	MATERIAL	QUANTITY (in gm)
1	Steel slag	1500
2	Clay	1500
3	Urea	485.64
4	Calcium Chloride	1191.46
5	Nutrient broth	12
6	Cocopeat	3%
7	Water	4000 ml

7.2 DISCUSSIONS

Fig 5.8: Batch reactor along with aggregates getting manufactured for 7th day test, provided with an additional loading on top.

This execution was a grand success in term of binding property and compressive strength. Thus, similar bricks were manufactured by varying reinforcement concentration, that would help in finding an optimum reinforcement concentration that will support the necessary compressive strength as per Indian Standard provisions. The manufacturing was done for 7 days. Similar trials were conducted by varying cocopeat concentration as well as using jute as reinforcement. The reinforcement concentration that showed maximum compressive strength at 7th day was chosen as the optimum concentration for 28th day testing.

7.3 TESTING OF BRICKS

The following tests was conducted in this study of bricks

- Compressive strength test
- Water absorption test
- Efflorescence test

7.3.1 COMPRESSIVE TEST

The compressive strength of bricks is an essential property that detrimental load bearing capacity. The surface of the bricks was cleaned from dusts and loose particles. The dimensions including length with and height of brick was recorded and cross-sectional area was calculated the brick was placed on Universal testing machine's lower plate ensuring its sits centrally and uniformly. The axis of the brick was aligned perpendicular to the loading direction and the load was applied at a constant rate of 14 Newton per millimetre square per minute until failure occurs. The maximum load or the load at failure was noted. The compressive strength of the brick was calculated by dividing the maximum load at the failure by the cross-sectional area.

$$\text{Compressive strength} = \frac{\text{Maximum load at failure}}{\text{Cross sectional area}}$$

Fig 5.9: Compressive strength testing in Universal Testing Machine

As per IS 1077:1992 clause 4.1;

- The acceptable minimum strength of burnt clay bricks is 3.5 MPa.
- The maximum strength of burnt clay bricks goes up to 35 MPa.

7.3.2 WATER ABSORPTION TEST

The water absorption test is a common method used to determine the porosity and permeability of brick. It helps to understand the ability of bricks to absorb and retained water is an important factor in determining its sustainability for various construction applications The final weight of the brick was noted and the water absorption was then calculated using the following formula:

$$\text{Water absorption} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \times 100$$

As per IS 1077: 1992, clause 7.2, bricks after immersion in cold water for 24 hours, water absorption shall not be more than 20 percent by weight up to class 12.5 and for the classes above 12.5 water absorption shall be between 12.5 and 15 percent.

7.3.3 EFFLORESCENCE TEST

Efflorescence refers to the white powdery substance that can form on the surface of concrete, masonry or any other porous material. It is caused by the migration of soluble salts to the surface, and react with moisture and form crystalline deposits. Efflorescence is typically white as well as shades of grey or yellow depending on the salts involved.. After this procedure, the brick was examined for efflorescence and the result was reported.

The efflorescence is reported only by qualitative words as follows:

- Serious- Salt deposition is quite heavy and increases with repeated wetting and drying.
- Heavy- Salt deposits cover more than 50 percent of the surface area.
- Moderate- Salt deposits cover 10-50 percent surface area. The salt forms thin layers without showing any tendency to peel off in flakes or become powdery.
- Slight- Salt covers the surface area of less than 10 percent and forms thin sticky layer.
- Nil- There is seen no deposit of any salt even after repeated wetting.

As per IS 1077:1976, the rating of efflorescence for up to class 12.5 bricks should not be more than moderate, for the bricks of class higher than 12.5, it should not be more than slight.

8 RESULTS AND DISCUSSIONS

This chapter discusses the result and inferences that is obtained from various tests. This also covers the role of reinforcements and its arrangement in bio-bricks and its effect in strength parameters. It also covers the comparisons studies on the different fibre reinforcements on strength of bio-bricks. The characterisation study of manufactured bio-bricks is also included in this chapter.

8.1 REINFORCEMENT – COCOPEAT

Randomly discrete arranged coir fibre can improve the compressive strength of a material through a process known as fibre reinforcement. When coir fibres are added to a composite material, and act as a reinforcement phase that helps to resist compressive forces. The randomly discrete arrangement of coir fibres allows them to distribute the compressive forces more evenly throughout the composite material, preventing localised stress concentrations and reducing the likelihood of cracking or failure. As a result, the material is able to withstand higher compressive loads before it deforms or breaks. In addition, coir fibres are naturally strong and stiff, that further enhances their ability to reinforce the material. The fibres also have good bonding properties, allowing them to adhere well to the surrounding matrix material and transfer loads more effectively. Overall, the addition of randomly discrete arranged coir fibre can significantly improve the compressive strength of a material and make it more resistant to deformation and failure under compressive loads. The bio-brick manufactured with cocopeat as reinforcement is shown in Figure 6.1.

Fig 6.1: Bio-brick

Table 6.1: Compressive strength of bio-brick on 7th day using different concentrations of cocopeat

Reinforcement (in %) - cocopeat	**1%**	**2%**	**3%**	**4%**	**5%**
Brick 1	3.58	4.55	7.53	6.04	5.06
Brick 2	3.82	4.93	6.79	5.67	5.43
Brick 3	3.95	4.07	7.28	5.92	6.04
Average Compressive stress (in N/mm^2)	3.78	4.52	7.20	5.89	5.51
Compressive stress (in N/mm^2)	3.78	4.52	7.20	5.89	5.51

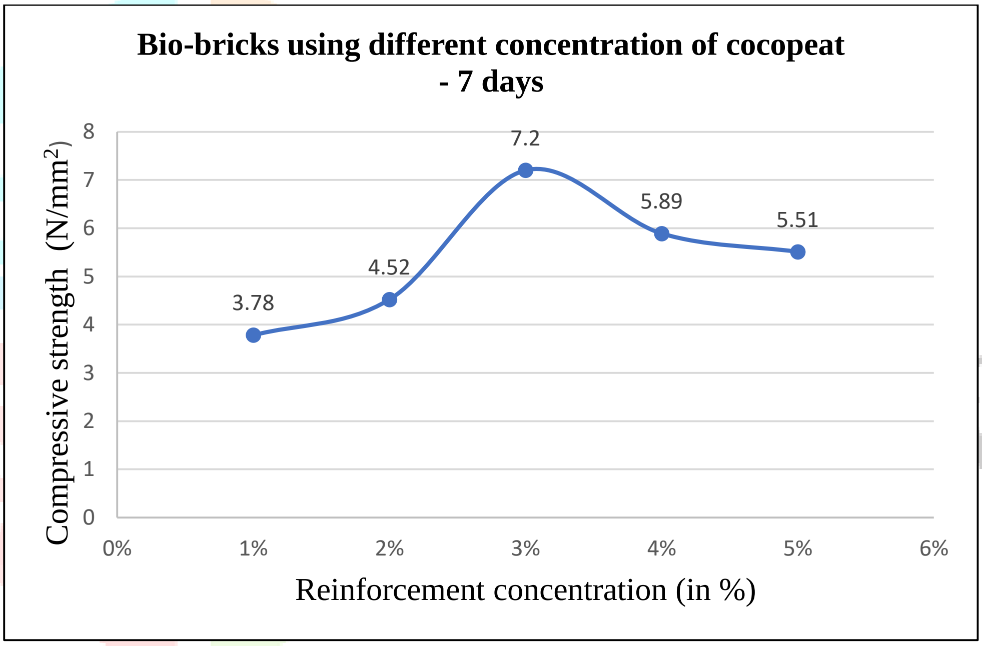


Fig 6.2: Graph showing variation in compressive strength of bio-brick using different concentrations of cocopeat

The results show the maximum compressive strength of bricks using cocopeat as reinforcement is 7.20 N/mm^2. This strength was obtained by the brick when added 3% reinforcement by weight. Natural fibre has an effect on the MICP process by interfering in the process. The interference increases drastically when the fibre is added 3%. Since the maximum compressive strength was obtained at 3% cocopeat concentration, it was chosen for the next run and tested their strength after 28 days. It was also noted that the further increase in cocopeat concentration reduced the compressive strength of the bio-brick. This was because, the excess amount of cocopeat fibres can increase the concentration of tannic acid in a base medium and makes the *Bacillus subtilis* inactive thereby interfering in the MICP process. Also, the addition of more cocopeat fibres contributed towards more void spaces, thus the compaction cannot happen efficiently. This also implies that the increase in cocopeat concentration do not always add to its strength, but there's always an optimum amount that shows maximum compressive strength.

Table 6.2: Test results of bio-brick on the 28th day using cocopeat

Brick 1	14.69
Brick 2	15.18
Brick 3	15.43
Average compressive stress (in N/mm^2)	15.10
Compressive stress (in N/mm^2)	15.10
Water absorption	15%
Efflorescence	Nil

- It is found that the compressive strength gets doubled after 28 days.
- Water absorption is 15% and is within the range.
- The efflorescence is nil.

8.2 REINFORCEMENT – JUTE

Jute was discretely arranged in the brick as it was found that it increases the compressive strength of the brick in several ways:

- Increased resistance to buckling: When jute fibres are arranged in a discrete pattern, it can resist buckling under compressive loads since it reduces the length-to-diameter ratio, making them more resistant to buckling.
- Enhanced confinement effect: The confinement effect is the ability of a material to resist deformation due to lateral pressure. When fibres are arranged in a discrete pattern, it create confinement around the material, reducing its lateral deformation and increasing its compressive strength.
- Improved load distribution: When a compressive load is applied to a material, it is distributed unevenly throughout the material. However, when fibres are arranged in a discrete pattern, it can distribute the load more evenly, reducing the stress concentration in certain areas and improving the overall compressive strength of the material.

Table 6.3: Compressive strength of bio-brick on the 7th day using different concentrations of jute

Reinforcement (in %)- Jute	**1%**	**2%**	**3%**	**4%**	**5%**
Brick 1	5.43	10.12	9.01	7.53	7.03
Brick 2	5.80	10.37	8.64	7.65	6.79
Brick 3	5.55	10.74	8.51	8.02	6.41
Average compressive stress (in N/mm^2)	5.59	10.4	8.72	7.73	6.74
Compressive stress (in N/mm^2)	5.59	10.4	8.72	7.73	6.74

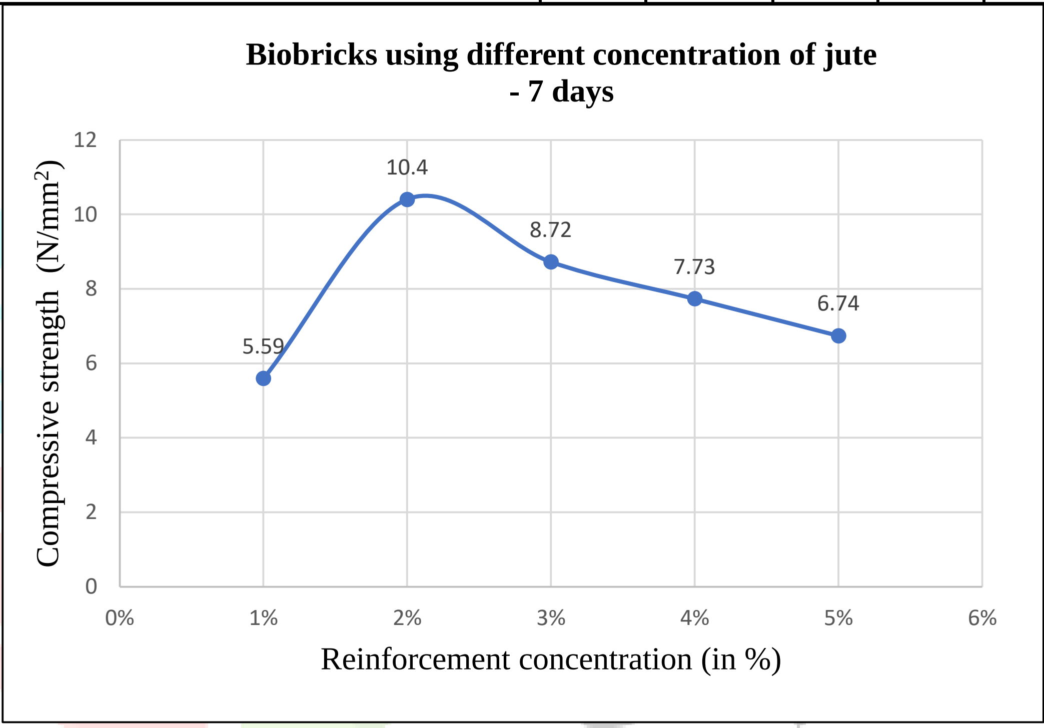


Fig 6.3: Graph showing variation in compressive strength of bio-brick using different concentrations of jute

- Jute fibres show an increase in compressive strength with an increase in the percentage of fibre added.
- The 2% of reinforcement (Jute by weight) taken for further manufacturing of bricks

The formation of cement gel causes it to occupy all the voids created around the jute fibres. And, it is further observed that the compressive strength of the bio-bricks goes on decreasing after a certain rise (2 %) in the fibre content. It is the result of the excessive fibre content, that may increase the number of voids or empty spaces within the bio-brick. The increase in the fibre content reduces the level of compaction thereby reducing the compressive strength of brick.

Bricks were manufactured by adding 2% jute and tested after 28 days

Table 6.4: Test results of bio-brick on the 28th day using jute

Brick 1	29.25 N/mm^2
Brick 2	30 N/mm^2
Brick 3	29.75 N/mm^2
Average compressive stress	30.08 N/mm^2
Compressive stress	30.08 N/mm^2
Water absorption	12%
Efflorescence	Nil

The compressive strength of bio-brick with jute is higher when compared with the compressive strength of brick manufactured with cocopeat.

8.3 WITHOUT REINFORCEMENT

Table 6.5: Test results of bio-brick on the 7th and 28th day without reinforcement

Day of Testing	**7th Day**	**28th day**
Brick1	1.85 N/mm^2	6.04 N/mm^2
Brick 2	2.2 N/mm^2	6.54 N/mm^2
Brick 3	2.34 N/mm^2	6.79 N/mm^2
Average compressive stress	2.13 N/mm^2	6.41 N/mm^2
Compressive stress	2.14 N/mm^2	6.42 N/mm^2

- The compressive strength is much lesser than the compressive strength of brick with reinforcement.
- Concluded that the brick shows more strength when adding reinforcement.
- Water absorption at 28th day is 11% with no efflorescence reported.

8.4 COMPARISON OF BRICKS

The comparison of bricks manufactured using jute and cocopeat as reinforcements, as well as the brick with reinforcement, is discussed in this section.

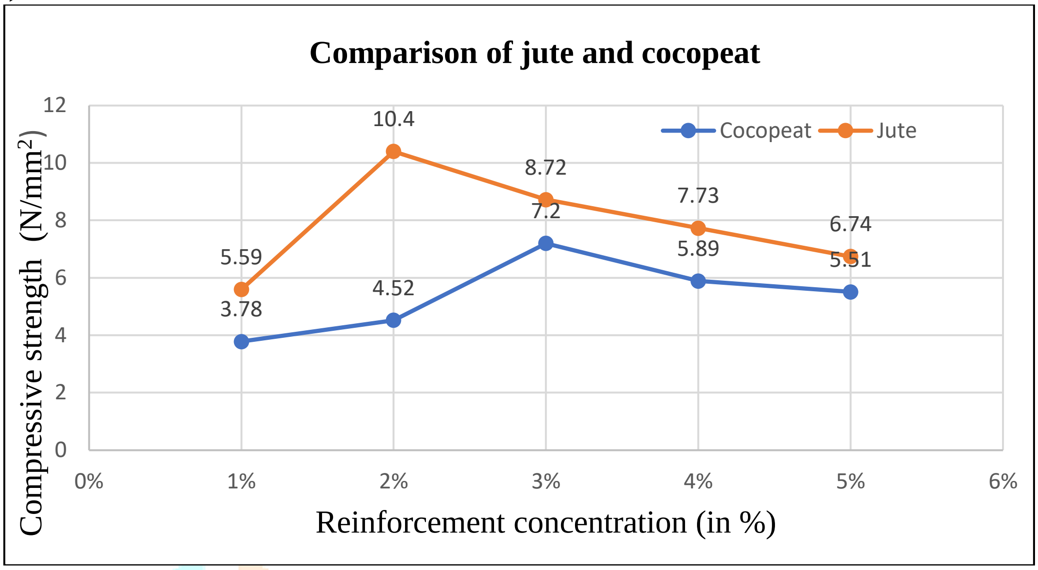


Fig 6.4: Comparison graph showing variation in compressive strength of bricks with jute and cocopeat - 7th-day

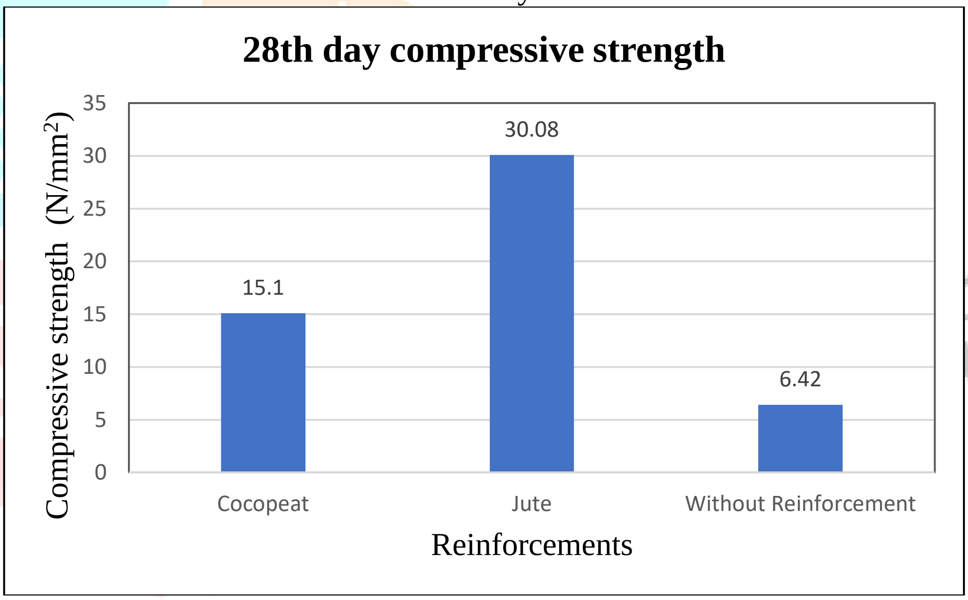


Fig 6.5: Comparison graph showing variation in compressive strength of bricks-28th day

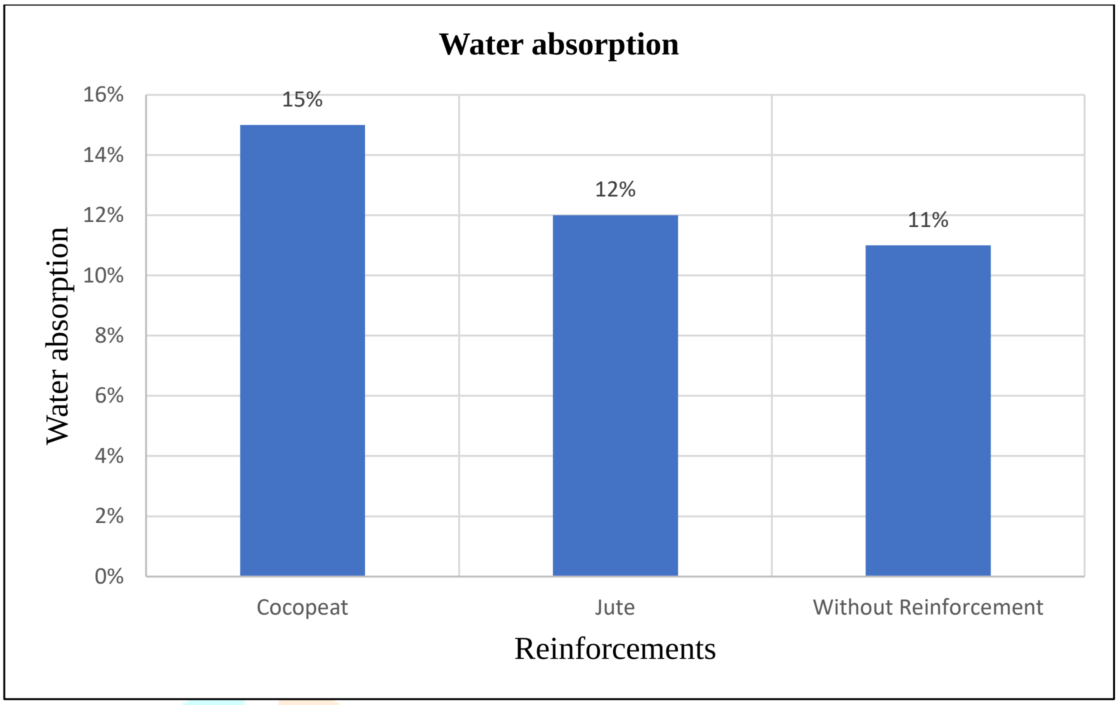


Fig 6.6: Comparison graph showing variation in water absorption of bricks-28th day

- The maximum compressive strength for jute was obtained at 2% and for cocopeat at 3%. Jute at 2% shows better compressive strength, followed by cocopeat at 3%, and then the one without reinforcements.
- Similarly, comparing the water absorption rates of the bricks, jute fibre reinforced brick has less water absorption compared to cocopeat reinforced, although both are within the limits of IS code. This is due to the water absorbing nature of cocopeat than jute.
- In both jute and cocopeat reinforcement bricks, efflorescence is nil, that is satisfactory.

8.5 CHARACTERISATION STUDY OF BIO-BRICKS

The characterisation study aims to characterise the micro structure and elemental composition of the brick using Scanning Electron Microscopy (SEM) and Energy Dispersion X-ray (EDX) analysis. The prepared brick sample was subjected to SEM imagine and examine its surface morphology, while the elemental composition was determined using EDX analysis. The results provide valuable insights into the structure and composition of the brick.

8.5.1 EDX ANALYSIS

The EDX analysis identified the elemental composition of the bio-brick, as it imparts a distinct signal for each element. EDX analysis of bio-bricks reinforced with cocopeat and jute are depicted in Figure 6.7 and 6.8. The presence of Ca, C and O was confirmed from the analysis report. The presence of $CaCO_3$ formed by MICP process that act as binding agent in between particles is thus supported by the occurrence of calcium, carbon and oxygen element in EDX pattern of bio-bricks reinforced with cocopeat and jute.

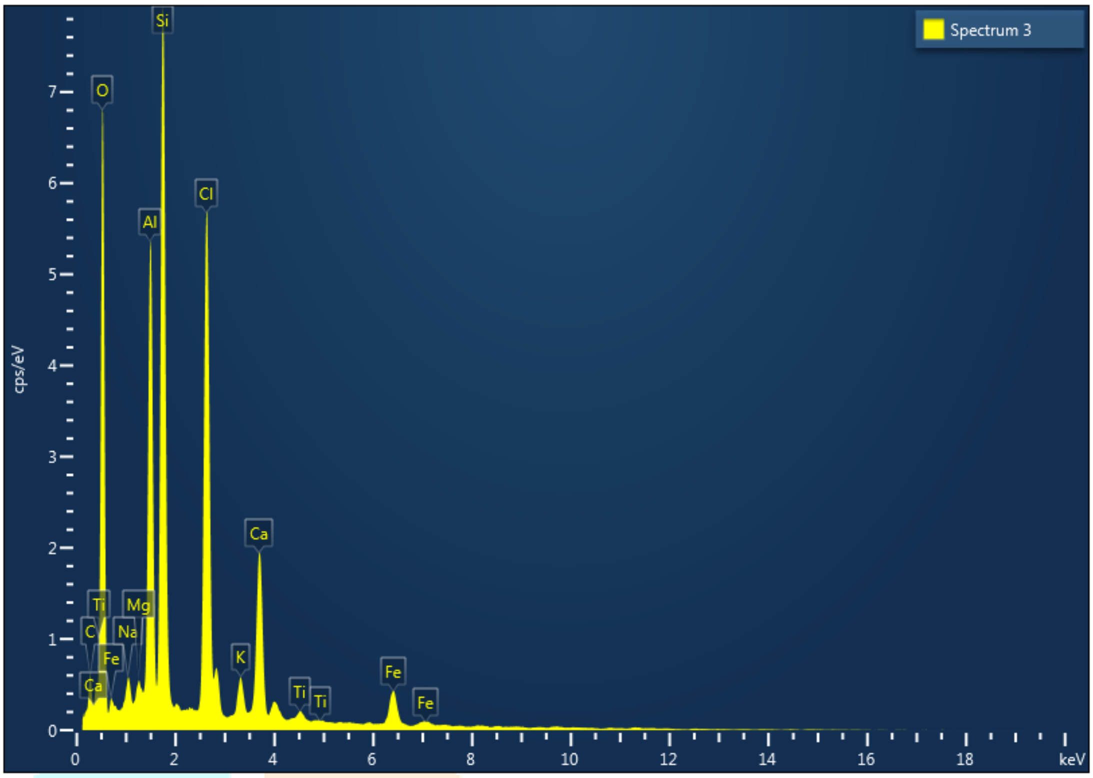


Fig 6.7: EDX analysis of bio-brick reinforced with cocopeat

Table 6.6: EDX test results of bio-brick reinforced with cocopeat

Elements	**Weight %**	**Atomic %**
C	11.45	18.53
O	45.56	55.38
Na	0.78	0.66
Mg	0.35	0.28
Al	8.02	5.78
Si	12.62	8.74
Cl	11.65	6.39
K	1.08	0.54
Ca	5.28	2.56
Ti	0.34	0.14
Fe	2.88	1
Total:	100	100

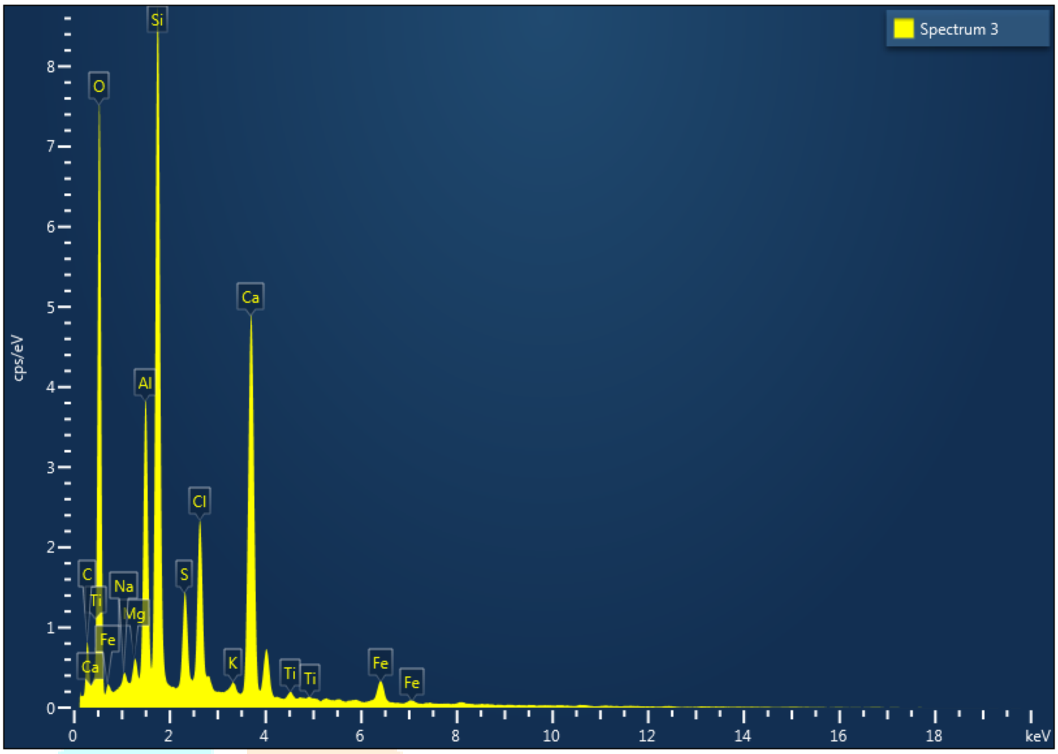


Fig 6.8: EDX analysis of bio-brick reinforced with jute

Table 6.7: EDX test results of bio-brick reinforced with jute

Element	Weight %	Atomic %
C	13.04	20.56
O	48.21	57.07
Na	0.36	0.29
Mg	0.49	0.38
Al	5.04	3.54
Si	12.07	8.14
S	2.01	1.19
Cl	3.96	2.12
K	0.28	0.13
Ca	12.17	5.75
Ti	0.43	0.17
Fe	1.95	0.66
Total	100	100

8.5.2 SEM ANALYSIS

SEM images revealed the surface morphology of the bio-bricks. The calcium carbonate precipitation on the surface of the brick can be clearly seen from the SEM images. The obtained SEM images shows the significant formation of rhombohedral crystals. The Figure 6.9 and 6.10 shows formation of calcite crystals on the surface of clay -steel slag particles. The rhombohedral crystals are indications of formation of calcite crystals (Wei Li et al., 2012). This calcite crystals helps to bind the particles together and in turn increase the strength. The cocopeat fibres and jute fibres are very visible on SEM images of the bio bricks samples that also helped in the increasing the strength parameters of brick.

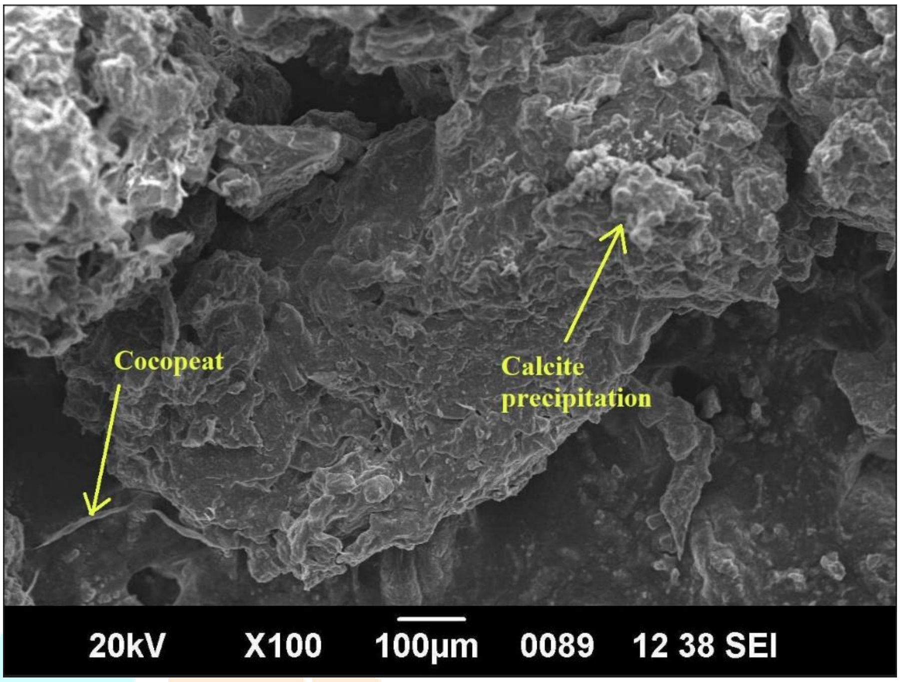


Fig 6.9: SEM image of bio-brick reinforced with cocopeat

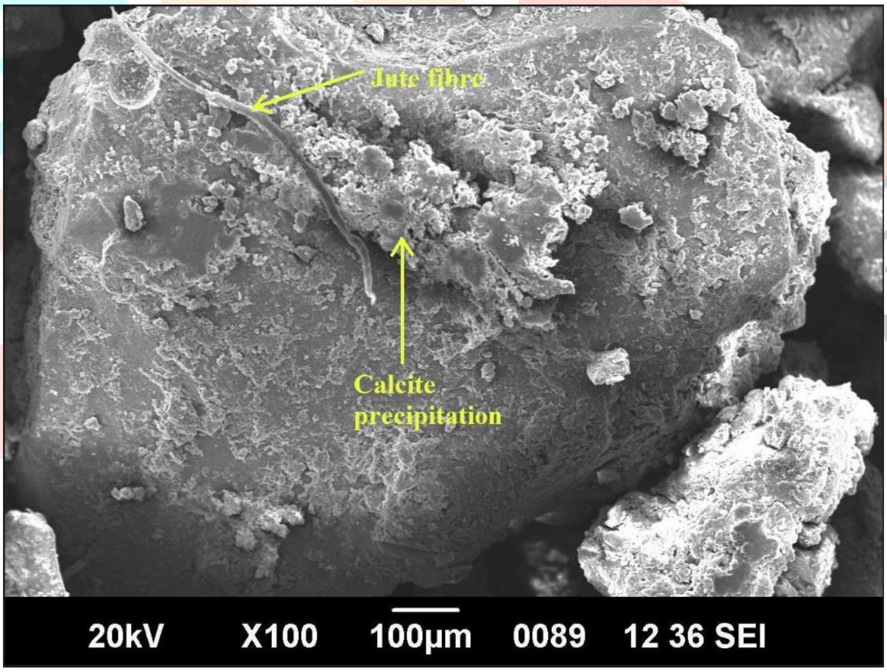


Fig 6.9: SEM image of bio-brick reinforced with jute

9 FUTURE SCOPES AND CONCLUSION

9.1 CONCLUSION

The cementation of sand into bio-brick materials through microbial-induced calcium carbonate precipitation (MICP) is a novel technology with broad applications. From the above experimental investigation, the conclusion can be summarised such that Calcium Carbonate precipitation is achieved in the brick combination of steel slag and clay by the MICP process.

The present study develops the strength of bio-mineralised steel slag and clay bio-bricks by using *B. subtilis* bacteria. It was observed that by increasing the concentration of *B. subtilis*, at 10^6 cells/ml concentration, the binding property as well as the rate of precipitation peaks. Strength increases with the addition of bacteria up to a certain cell concentration but after or before cell concentration strength of the brick decreases. Calcium Carbonate precipitation can act as a binding agent in between the aggregates. The compressive strength of the MICP-treated bio-bricks was tested through brick compressive strength test. Additives including discrete randomly distributed fibres, steel slag and clay were provided to reinforce the compressive strength of bio-bricks. Results concluded that the addition of synthetic and natural fibres can increase the compressive strength of the bio-bricks. Bio-bricks strength development was also achieved by adding a nutrient broth medium supply.

The initial trials proved the biocompatibility of base aggregates, fibres and polyurethane with *Bacillus subtilis* and the trials also helped to determine the right composition of cementation medium, and base aggregates and also helped to understand the role of buffers such as Ammonium Chloride and Sodium Bicarbonate, nutrient broth in maintain the basic pH in cementation medium and how it helps to keep the bacteria active throughout the process. It also helped to determine the optimum arrangement of batch reactors and surcharge loading mechanism. The initial trials also helped to understand the effect of tannic acid produced by coir and its impact on Bacillus subtilis and ways to overcome it.

The experiments also helped to determine how different percentages of cocopeat fibres and jute can affect the compressive strength of brick with compressive stress peaking at 7.20 N/mm^2 at 3% of weight for cocopeat fibres and the compressive stress peaking at 10.4 N/mm^2 at 2% of weight for jute bio-bricks. The jute fibres reinforced bio brick has 44.44% higher compressive strength than cocopeat fibres reinforced bio brick at its peak compressive strength. The integrated findings of EDX and SEM proved the process of MICP and confirmed the formation calcite in the bio-bricks.

In future, sustainable and smart materials could be added to enhance further the properties of bio-bricks that can play an important role in carbon footprint reduction. This can be an economical process as well as it imparts sustainability in the field of construction.

9.2 FUTURE SCOPE

MICP (Microbially Induced Calcium Carbonate Precipitation) mediated brick manufacturing process is an innovative technology that uses bacteria to produce a natural cementing agent that can bind soil particles and create strong and durable bricks. This technology has several potential benefits and future applications in the field of construction.

One potential application is in the production of sustainable housing in developing countries. The MICP process can use locally available soil and bacteria, that makes it a cost-effective and accessible technology for producing building materials. This can help to address the housing shortage in many developing countries and provide affordable housing to low-income families.

The research has the potential to use locally available natural fibres to enhance the engineering properties of brick. It has the potential to reduce the number of days required to attain full strength by mutating the bacterial cell. Further studies are required to understand how different sizes of aggregate and base materials can affect the different engineering properties such as compressive strength, permeability, etc...

9.3 FUNDING

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