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Self-healing Coal fly ash Construction Brick for CO2 and Dust Adsorption

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ABSTRACT

As a common byproduct of thermal power plants, coal fly ash (CFA) is often dumped in landfills, where it can cause environmental damage. As a result, in this work, porous construction bricks were made utilizing a byproduct of a thermal power plant, coal fly ash, and baking yeast to absorb carbon dioxide and dust. Yeast was utilized for pore formation, CFA detoxifying, and crack repair. The physical properties of prepared porous bricks are characterized using .X-ray diffraction (XRD), scanning electron microscopy (SEM), confocal microscopy (CM), and Fourier transform infrared spectroscopy (FTIR) According to the XRD analysis, the brick is made up of quartz, hematite, and mullite. The Porous Brick absorbed 36% of water and 2.5% of dust. The porous fly ash brick has demonstrated superior strength (17.5MPa) and load bearing capacity as compared to traditional bricks in compressive testing. For analysis of the fly ash bricks' ability to absorb carbon dioxide, a gas chromatograph equipped with a Flame Ionization Detector (FID) was utilized. A high adsorption capability of 94.69 percent of CO_2 was found for the produced geopolymer bricks. The yeast involvement promote and facilitates the self-healing ability of the coal flay ash brick (CFB).

1 Introduction

As a fuel source, coals are important to both domestic users and the plethora of industries that rely on them. Fly ash is a byproduct of the coal-based energy production at thermal power plants. More than five million tons of coal fly ash (CFA) are produced worldwide every year, with much of it ending up in landfills [1, 2].

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Because CFA contains metals (Hg, Cd, Ar, Pb, Cr, and Se) that are toxic to the environment and human health over time, the soil and water around CFA disposal sites can polluted and become contaminated over time [3, 4]. Many researchers have looked into ways to use coal fly ash to create eco-friendly materials in an effort to lessen the impact of CFA. Preparing different Geopolymer for structural application is one of the many ways CFA is put to use [5]. Industrial wastes like CFA are suitable for geopolymer formation because they already contain high contents of Silica and Alumina, unlike virgin raw materials (natural minerals and calcined clays). To remove CO2 from the air, geopolymer can be used as a solid adsorbent.

Carbon dioxide is a major contributor to climate change and global warming because it is a greenhouse gas. Because of their ability to lower atmospheric CO2 levels, carbon capture and storage technologies will play a pivotal role in facilitating global transformation. In order to capture CO2 using porous materials with high surface areas, one of the many mechanisms available is physical adsorption [6].

The alkaline activation of alumino silicate produces geopolymers, which are three-dimensional amorphous networked structures formed below 100°C. High surface areas, porosity, and active sites are necessary characteristics of a sorbent for CO2 adsorption efficiency [7]. Carbonation reaction could be aided by the presence of CaO and MgO in the geopolymers [8, 9]. In addition, CFA bricks can be used in the construction of roads, pavements, dams, and bridges because they are lighter in weight and have better mechanical properties than traditional clay bricks [10]. Greater compressive strength and a wide range of applications characterize porous structural materials [11]. Because of this, pore-forming agents can be used to create void defects in the brick of varying shapes and sizes, thereby enhancing the brick's mechanical properties. The use of pore-forming agents in the production of porous ceramics and polymers is a well-established technique [12].

For the manufacture of porous ceramic materials, the use of a biological pore-forming agent, such as yeasts, has been documented [13]. To create a macro-porous structure where the pore morphology can be managed, yeast is used as the pore-forming agent [14, 15]. To add to that, yeast cells can be used as a pore-forming agent in conjunction with sugar, water, or other fluids to generate a porous polymer. The CO2 gas bubbles formed by the yeast cell reacting with the sugar lead to the creation of permanent pores within the polymeric material bricks [16, 17]. In addition, yeasts are promising agents for the removal of heavy metals from subsurface environments [18]. Metal cations and negatively charged yeast cellular compounds interact physiochemically, leading to adsorption [19].

It is important to consider the long-term viability of building materials, in addition to recycling for practical applications. Here, waste (CFA) and yeast were used to create porous building bricks that were found to be able to absorb 98.5% of CO2 and 2.5% of dust from the surrounding environment. Water absorption is 36% and compressive strength is 17.5 MPa in this porous brick.

2 Experimental Procedure

In this study very fine coal fly ash (CFA) burned from Indian bituminous coal were collected from Gandhinagar thermal power plant, India and baking yeast (Saccharomyces Cerevisiae) were used as raw materials for fabrication of porous bricks as shown in Figure. 1. All the CFA samples were used as-received without any treatment.

Porous fly ash brick samples were prepared by mixing sugar and yeast, which have 15% concentrations each, with the coal fly ash powder and result in viscous slurry. Then the slurry was poured into a plastic mould and allowed to stay for 3 hours at room temperature in order to favor fermentation. This allows the yeast to grow and increase their activity for foaming the slurry [17]. The slurry was allowed to dry in programmable laboratory furnace chamber at 800C for 10 hours and allowed to cool slowly inside the furnace. Finally, porous fly ash based bricks (PFB) were removed from the mould and shown in Figure 1c.

The XRD pattern was recorded on a BRUKER D8 DISCOVER X-ray diffraction instrument (Cu, K-β filter, 49kV and 40 mA) to check mineralogical phases present in CFA powder sample. SEM investigations were conducted in FE-SEM-JEOL JSM7600F to observe the microstructural of the raw materials and porous bricks.

Confocal images were also taken using Confocal Microscopy (Leica TCS SP8). The as-received CFA and the PFB sample were characterized using FTIR spectroscopy (PerkinElmer FTIR Spectrometer Spectrum Two) to check their functional groups.

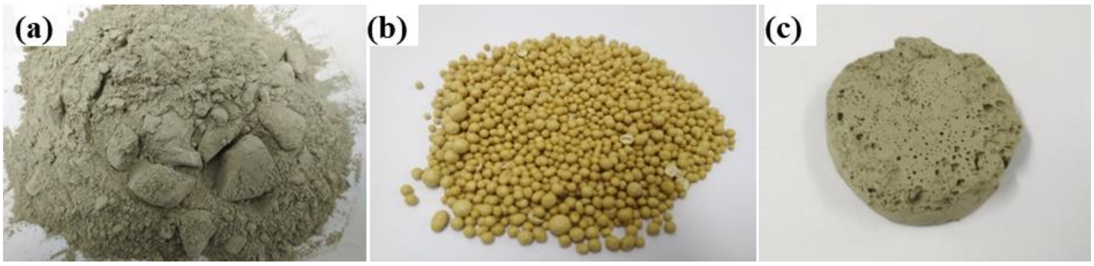

Fig. 1 – Raw materials and prepared porous fly ash bricks; (a) Coal fly ash powder, (b) baking yeast, (c) Porous fly ash brick sample Equations

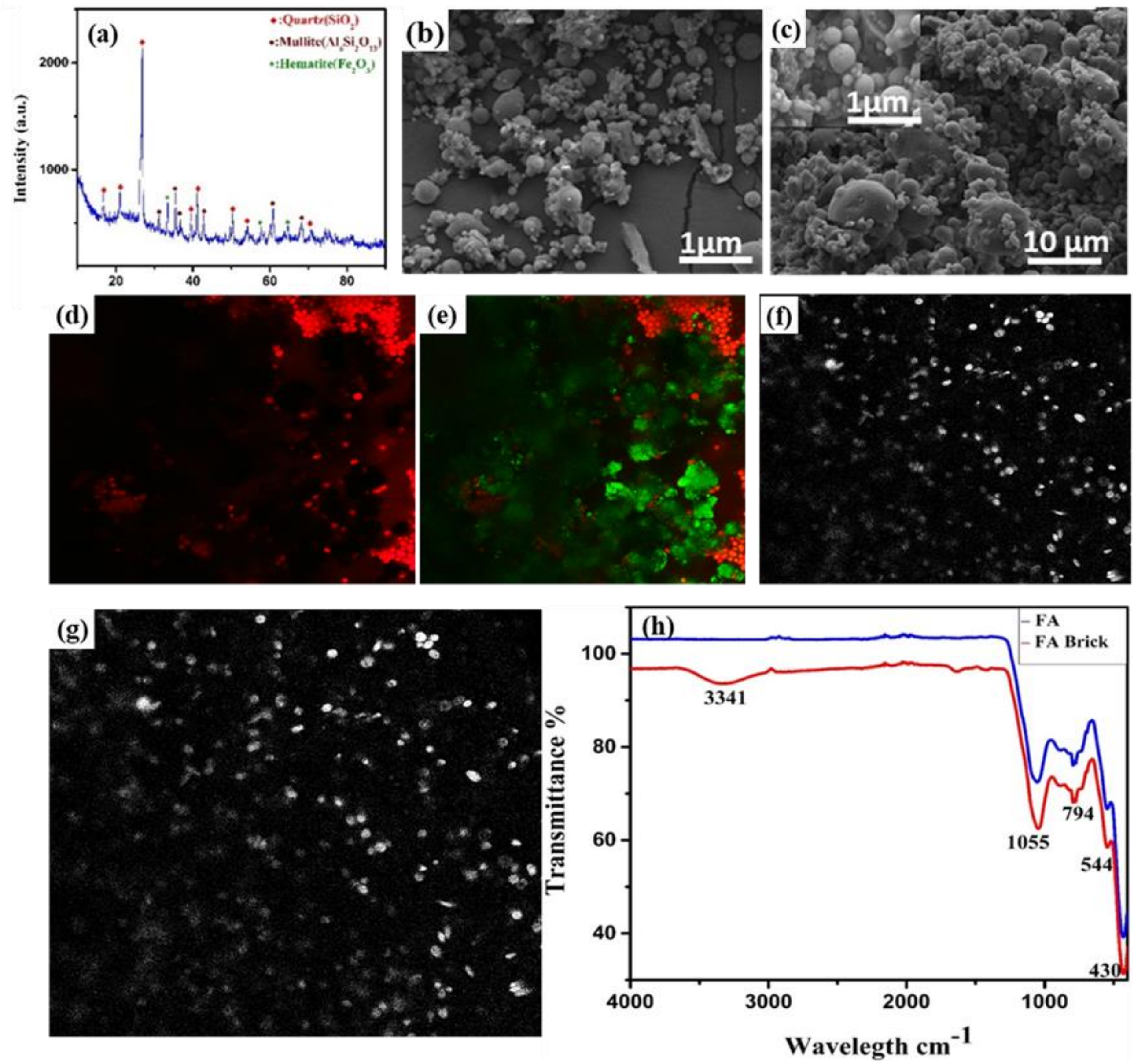

Fig. 2 – Mineralogical, Microstructure & Functional Group of CFA and Yeast cell; (a) XRD pattern for the coal fly ash brick, (b) FE-SEM images for Coal fly ash powder seen as irregular round-shaped and spherical particles, (c) FE-SEM images for Porous fly ash brick, (d) Yeast cells in the Propidium iodide solution (e) Powder of PFB in the Propidium iodide solution (f-g) Differential Interference Contrast (DIC) microscopic image of yeast cells and PFB solution respectively, (h) FT-IR spectra of samples (FA-the as received coal fly ash, FA brick-porous fly ash brick).

Compressive strength of the porous brick samples were measured using a Universal testing machine (UTS Systems, CMT5105), and the contact angles were also measured using sessile drop method as well as using Drop Shape Analyser (DSA25) KRUSS instrument. Distilled water and yeast solution was used for the analysis of contact angle. Eutech pH meter was used to measure pH for the solution of fresh fly ash and PFB sample.

We measured water absorption of PFB samples to check the durability of the specimens according to ASTM C20-00 (2015). Dust absorption studies were also carried out on PFB sample by measuring the percentage change before and after dust addition.

Fly ash based-geopolymer bricks were prepared by simple gel method initially by using some portion of PFB sample and KOH alkaline solution then the geopolymer is used as a raw material for CO_2 adsorption test. The geopolymer bricks were used without any heat treatment for CO_2 adsorption study which was analysed by a gas chromatograph (CIC Baroda) using a Flame Ionization Detector (FID).

3 Results and Discussion

3.1 Mineralogical and Microstructural Characterization

Figure 2(a) is an XRD pattern of a coal fly ash brick that shows the primary compounds to be quartz (SiO_2), hematite (Fe_2O_3), and mullite ($Al_6Si_2O_{13}$), which is consistent with the previous study report [20].

Images taken with a scanning electron microscope (figure 2(b)) reveal that the particles in the coal fly ash are not uniform in size or shape. The SEM image of a porous fly ash brick is shown in Figure 2(c), and the irregular round particles in the fly ash powder may be the result of unburned carbon (c). The photograph reveals that the brick surface is made up of both perfectly round and irregular spheres.

Confocal images of a sample of yeast and PFB solution revealed small circular red spots in the yeast solution (Figure 2(d)). A cluster of yeast cells might be responsible for the red spot. Yeast cells in the PFB solution appeared as red spots and were evenly distributed across the fly ash's green background. 2 (e). Figure 2(f&g) shows DIC micrographs of a yeast cell and PFB solution respectively, demonstrating that the yeast cells survived after dehydration caused by the heat treatment. This is due, blending yeast cell with sugar can replace water molecules and help to survive by preserving their structure and activity of cell components during dehydration without death [21].

The infrared (IR) bands of the fly ash and porous brick samples as received are displayed in Figure 2(h). The as-received fly ash sample has distinctive peaks at around 1055cm^{-1}, caused by asymmetric stretching vibrations of Si-O-Si, and a band at around 794cm^{-1}, which is the Si-O symmetric stretches. Minor shoulder peaks at around 544cm^{-1} and 430cm^{-1} may be associated with anhydrite, aluminum in tetrahedral positions, and O-Si-O bending vibrations. The stretching vibration of OH– groups in water molecules was detected as a peak at 3341cm^{-1} [22, 23].

3.2 Mechanical and physical properties of PCFB samples

As can be seen in figure 3, we used a load-displacement curve to calculate the compressive strength of PFB samples (a). Due to the porous nature of the brick, the load-displacement curve was nearly constant for about 7 mm, demonstrating large load-bearing with little displacement compression. The compressive strength of the sample increased to 17.5 MPa once the particles/porous became dense and no further displacement of particles in the brick. Bricks with a minimum compressive strength of 10.34 MPa for normal weathering and 17.23 MPa for moderate weathering are required by ASTM C62-13 [24]. As a result, the PFB of the compressive test result satisfies the criteria for standard bricks and can be used for building construction.

Porous brick measured 44.06 degrees (as depicted in fig. 3) in terms of contact angle (b). High wettability is indicated by a contact angle below 90 degrees, while hydrophobicity is indicated by an angle above 90 degrees [25, 26]. That the bricks' surfaces are wettable for water but hydrophobic for yeast solution was established by measuring the contact angle of PFB. Because yeast solution is so viscous, the PFB bricks' surfaces have a greater contact angle with it.

As-received fly ash (FA) had a pH of 8.62, indicating its alkaline composition. While the pH of the solution containing PBF powder was measured at 6.14, the pH of the FA solution dropped after the bricks were made due two basic reasons. Yeast cells fermenting in the presence of a trace amount of sugar causes the pH to drop. Fermentation produces acids which cause a decrease in pH. Another reason can be absorption heavy metal ions by yeast cells which is called bio sorption .Heavy metal ion absorption by yeast cells is another theory for the pH drop [27].

After 24 hours, as shown in Figure 3, all of the fragments of the crushed PFB brick samples were connected and had self-healed (c). The yeast cell can survive on dehydration due to it contain small sugar. Adding sugar substitute water molecules and form glasses which maintain the structure during dehydration and helps them to continue their viability during dehydration [2] and resume normal life once again upon rehydration [28], is responsible for the self-healing process. In this case, the molecular structure of the plasma membrane was responsible for the observed phenomenon. Yeast cells' phospholipid membranes dry out during the dehydration process, compromising their structural integrity and their ability to carry out their metabolic functions. The yeast cell's membranes go through a transition from the gel to liquid crystal phase during rehydration, allowing the cell to resume its active life. The yeast's ability to endure dehydration and rehydration allows for the repair of brickwork that has suffered cracks. [29, 30]. The 917 Kg/m^3 density of the finished PFB brick is lower than that of typical building brick [24].

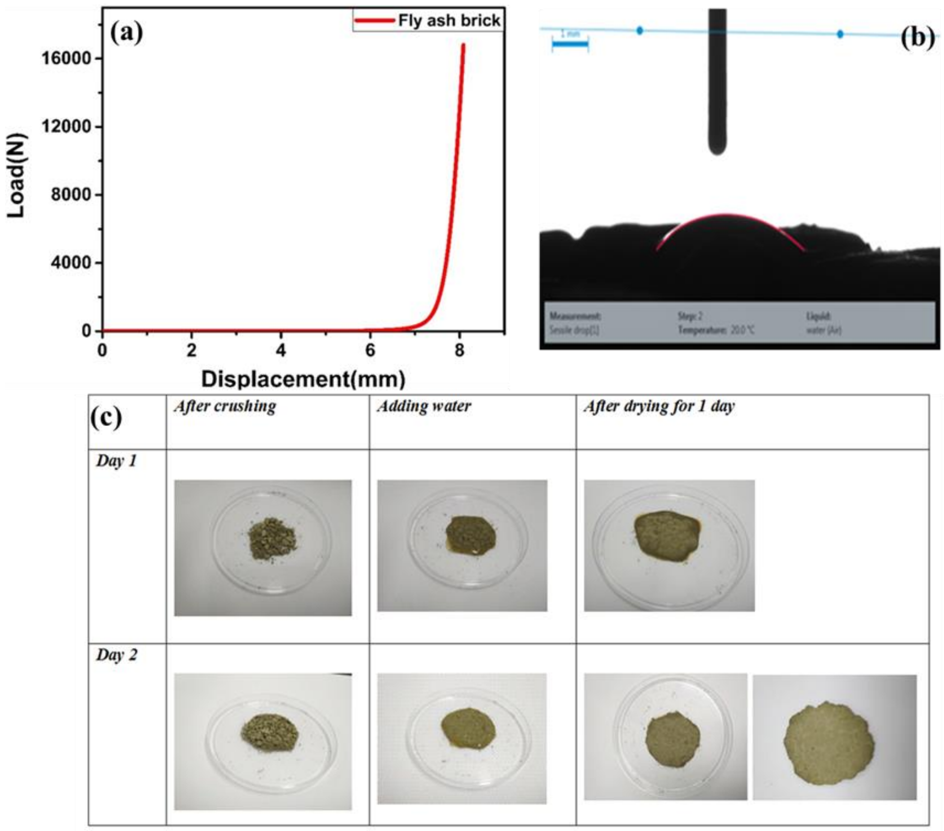

Fig. 3 – (a) Load-displacement curve of porous fly ash brick, (b)Contact angles values of porous bricks samples using water and yeast solution, (c) Demonstration of interconnecting fraction of porous fly ash bricks (PFB) crushed in to fraction(Day 1) and up on adding water the fraction interconnected each other at room temperature and keep on crushing (Day 2).

3.3 Fire Resistance, Water, Dust & CO2 Absorption of PCFB

Water uptake in porous construction materials is a result of capillary action. If the liquid is thicker, it will have less of an effect on the surfaces it comes in contact with. After preparation, PFB samples absorb 36% of their weight in water. Bricks can have an acceptable water absorption percentage anywhere in the range of 20%-30% [31]. Extremely porous bricks may crack easily due to the volume changes caused by water absorption. Low absorption is also undesirable because water that runs off the roof is not absorbed by the bricks and can damage the mortar joints [32]. Therefore, the prepared PF brick's percentage of water absorption is within the acceptable range.

Fine dust particles were exposed to the prepared porous bricks to measure their ability to absorb the particles. After being exposed to the dust, the brick gained 2.5% in weight. A 4.5 percent loss in weight was recorded for the porous brick sample during the fire resistance test, which was conducted to evaluate the samples' resistance to fire penetration and to measure the samples' ability to retain integrity after firing. The prepared porous brick demonstrates excellent fire resistance ability, as evidenced by the small amount of weight loss experienced after firing. Fly ash's high concentration of reactive silica promotes the formation of aluminosilicate gel and aids in the development of geopolymer. Ion exchange properties are imparted to the geopolymer matrix via an amorphous network of SiO_4(and AlO_4(tetrahedral units that form rings of various sizes. For this reason, CO_2 adsorption is just one of many potential uses for geopolymers [32, 33]. Therefore, we used the PFB sample to research geopolymer's CO_2 absorption.

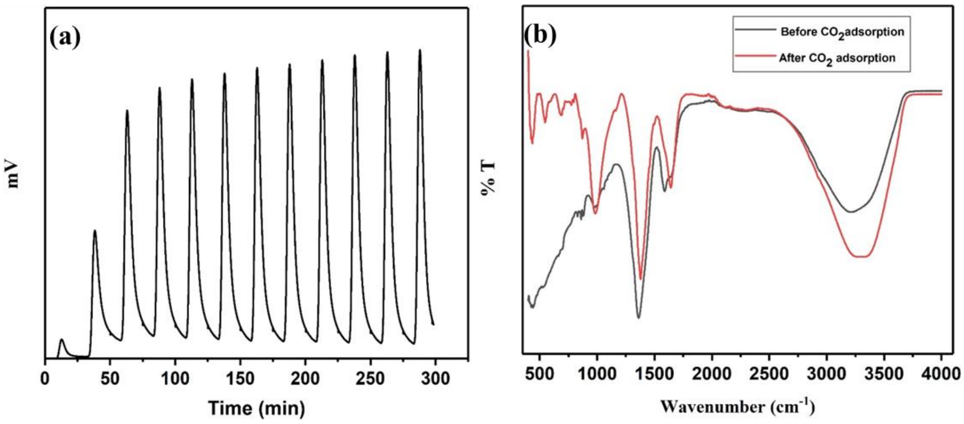

Fig. 4 – CO_2 adsorption study by using Flame ionization detector (FID) in Gas chromatography (a) CO_2 is injected in pulse mode (1 ml/ 25 min), (b) FTIR spectrum of geopolymer, before and after the CO_2 adsorption study.

The synthesized geopolymer shows maximum adsorption of 94.69 % in the first cycle of CO_2 pulsing. Then the material gets saturated gradually with CO_2 on its surface. Within each cycle, adsorption decreases & complete saturation occurs after eight cycles of 200 min as shown in table.1 and figure 4(a). A few studies showed that there is a relationship between the CO_2 adsorption capacity with the concentration of essential basic sites on geopolymer composition, the reaction between the acidic carbon dioxide and a higher concentration of available essential basic sites from the used alkaline solution and fly ash will increase the adsorption capacity geopolymer [7].

Table 1 – Injected CO_2 in pulse mode (1 ml/ 25 min) and % of CO_2 adsorbed.

Cycle no.	Time (min)	% Adsorption
1	25	94.69
2	50	56.38
3	75	10.75
4	100	5.73
5	125	5.08
6	150	3.71
7	175	3.27
8	200	2.03

It is evident from the Gas chromatographic study that this geopolymer is capable of absorbing CO_2. FTIR measurement for the geopolymer before and after the CO_2 adsorption test was done and shown in the figure 4. (b). If this is a case of physical absorption, all three bands due to CO_2 will be observed in its FTIR spectra, namely, (a) one at 2349 cm^{-1} due to asymmetric stretching of C=O bond, (b) another at 667 cm^{-1} due to weaker double degenerate C=O bending and finally (c) another at 1388 cm^{-1} due to symmetric stretching of C=O, would have been observed,. None of the bands were observed. So we may rule out the possibility of physical adsorption. But there is some depletion and rise of peaks before and after CO_2 absorption. This strongly suggests that this is a case of chemisorption. After CO_2 adsorption, a new peak at 981 cm^{-1} emerges, which may be assigned to = C-H bending. This peak at 981 cm^{-1} may also be assigned to carbonate ion. Another possibility is, a little excess of alkali used in the synthesis of the geopolymer is still present in the system and absorbing CO_2. However it is very difficult to find out what mechanism contribute most in the absorption of CO_2.

4 Conclusion

Baking yeast and CFA can be used to make porous bricks for use in construction. As opposed to conventional brick processing methods, this method uses very little energy and produces high quality bricks. While making porous coal fly ash bricks, yeast cells play an important role. The CFA bricks achieved 17.5MPa in overall strength, a crucial metric for construction bricks, allowing them to be used in mild climates. To make porous bricks, yeast is used as a foaming, self-healing, and pore-forming agent. CO_2 and dust were absorbed by the porous structure of bricks made from CFA and yeasts. In the first cycle, the brick is able to absorb 94.69 percent of CO_2, while in the second cycle, it can only absorb 56.38 percent. As a result, areas with high carbon dioxide emissions may benefit from the use of CFA porous bricks in construction.

Also, after being exposed to a dust environment, bricks gain 2.5% of their original weight due to the fact that their porous structure allows them to absorb dust and fine particles. Yeasts have impacts on reducing the toxicity of CFA because they changed its low alkalinity to a nearly neutral pH value by adsorbing heavy metal ions and fermenting. Yeasts are able to form carbonate precipitation, which allows them to survive in a dehydrating and rehydrating environment. Cracks in brickwork can be repaired by the carbonate precipitates produced by yeast cells. Therefore, applying only water to bricks samples with yeast cells added early in the preparation process has an advantage in curing damages.

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