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Effect of Zeolite in the Mechanical Properties of Concrete and its CO_2 Absorption Characteristics to Form an Eco-Friendly Environment

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Abstract

Carbon dioxide is one of the major air pollutants into the atmosphere. Carbon dioxide is emitted more into the atmosphere because of combustion of fossil fuels (coal, oil and natural gas) in cement production industry and many other industries and emissions from traffic congestions. Carbon-dioxide pollutes the air and the air pollution is the major threat faced by the present generation. Hence, there is a need to have an eco-friendly concrete which can absorb the carbon-dioxide from the atmosphere and reduces the air pollution. Therefore, a study has been carried out on the zeolite concrete for the enhancement of the mechanical properties and on the absorption of carbon sequestration in to the zeolite concrete.

Keywords: Zeolite • Carbon dioxide • Air pollution • Eco-friendly • Sequestration • Strength

Introduction

With the increase in population, the demand for the construction increases. Thereby the production of cement based construction materials increases which emit more Carbondioxide into the atmosphere. Also with the increase in population the demand for the own vehicle increases. This leads to more vehicle emissions of Carbondioxide and other toxic gases into the atmosphere and pollute the atmosphere. Among all greenhouse gas emissions, carbon dioxide (CO_2) emissions are considered as the most serious concerns [1]. Carbon-dioxide, the main greenhouse gas emission, traps heat in the atmosphere and contribute to climate change. There exists an urgent need for the recovery or reduction in CO_2 emissions or recycling of CO_2 and effective utilization of Carbondioxide. CO_2 from the atmosphere is to be trapped and deposited in a reservoir either beneath the earth or under ocean or on the construction material is known as the carbon sequestration [2]. The capacity for carbon capture and storage (CCS) in geologic formation is approximately 1 million tonnes per year per site [3]. Carbon-di-oxide may be utilized in concrete blocks and bricks production as equivalent to carbon sequestration [4]. The direct and indirect emission coefficient of Carbondioxide from cement industry is 58.2% [5]. Trees and plants play a major role as absorber of the Carbondioxide through photosynthesis [6]. Because of urbanization, many green lands were replaced with several cement based constructions. Therefore, it is important to absorb large volume of carbon dioxide from the atmosphere in cement based structures other than the trees. Hence the need for these cement based structures are to be designed to minimize the Carbondioxide emissions from the structure and serve other useful purposes in addition to shelter as shown in Figure 1.

The Carbondioxide may be sequestered in the cement or lime based products in order to reduce the CO_2 in the environment [7] via carbonation process. Carbondioxide slowly diffuses through the pores present in the cement or lime based products and react with the calcium compounds to form a stable calcium carbonate i.e., Carbonation as shown in Figure 2.

With the increase in the concentration of CO_2, carbonation increases significantly [8]. Carbonation depends upon the pore structure and occurs in the pores near the surface of concrete and progresses interior of concrete [9]. This results in the modification of pore refinement in the cement paste. The diffusion of carbon-di-oxide becomes difficult as it diffuses further in the cement paste matrix, which results in reduced rate of carbonation of

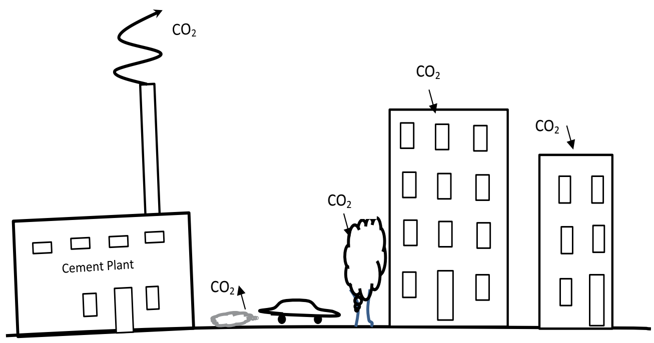

Figure 1. Carbon dioxide emission into the atmosphere.

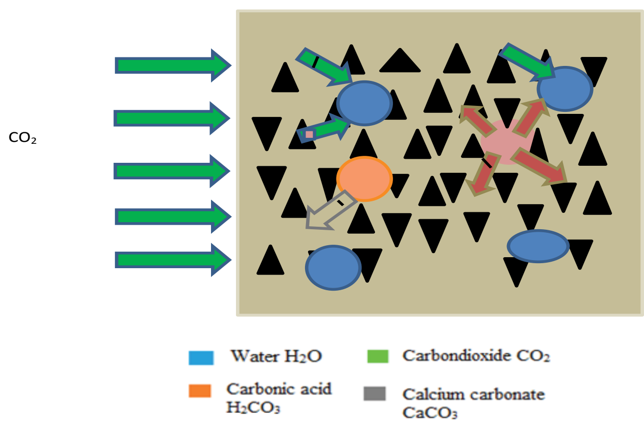

Figure 2. Carbonation in concrete.

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cement-based products. The factors that influence the carbonation are, the moisture content, temperature relative humidity, CO_2 concentration and the availability of Ca $(OH)_2$, water and the replacement of cement with mineral additives [10]. Zeolite is the largest group of silicate minerals stated in the minerals database. Some of the mineral zeolites are analcime, chabazite, clinoptilolite, heulandite, natrolite, phillipsite, and stillbite [11,12]. It was found that zeolite consist of a crystalline structure bonded together in such a way that it form a tetrahedron structure zeolite and hence it can be considered as an active admixture which contributes to the formation of microstructure and can improve the properties of hardened concrete [13-16]. The mixed matrix membrane of polymer and zeolite as the most effective membrane for post- combustion CO_2 capture and zeolite offers CO_2 adsorption capacity and it increases with increasing pressure and decreases with increasing temperature [17,18]. The research identified that the traffic as being the top contributor for air pollution. With the increase in the demand for the vehicles, it leads to more traffic. With the traffic congestion, the average traffic speed reduces which emits more CO_2 into the atmosphere. At low speed, scientific studies reveal, vehicles burn fuel inefficiently and pollute the environment for every trip [19,20]. Incorporation of zeolite into the concrete is one of the most promising concepts to absorb the Carbondioxide from the atmosphere [21]. The study has been carried out on the zeolite, zeolite mortar and the zeolite concrete for its mechanical properties and the carbonation study has been carried out on the zeolite concrete for the Carbondioxide absorbtion in order to have the eco-friendly environment.

Materials and Methods

In this study, the zeolite material properties and four mixtures of 1:3 cement mortar were prepared in 70.6 × 70.6 × 70.6 mm cube with distinct ratios of the zeolite as substitution of M-sand aggregate (mass with volume compensation), considering the amounts of 0%, 10%, 20% and 30% as shown in Table 1. The compressive strength of mortar was studied with 0%, 10%, 20% and 30% of zeolite replaced with M-sand in the cement mortar cube for 14th , 21st and 28th day test. Then the study was carried out on M15 zeolite concrete for compressive strength and for the carbon sequestration in zeolite concrete.

Material properties

Physical properties are the characteristics that are observed or measured without changing the composition of substances. The physical properties of zeolite were studied with its colour, texture as shown in Figure 3, pH value as shown in Figure 4, internal temperature using probemeter as shown in Figure 5, microstructure study and its composition in XRD as shown in Figures 6-8.

Zeolite is Greyish white with smooth texture. pH value indicates the material as acidic or alkaline. pH value was determined using pH strip as shown in Figure 4. The pH value of zeolite was observed as 8 (green) which indicated that the zeolite can be used in concrete as it is alkaline in nature. The internal temperature of the zeolite was measured as 26°C and hence the effect the hydration of concrete is negligible.

Physio-chemical characterization and structural examination

The crystallographic properties of zeolite concrete were studied by X-ray diffraction. The morphology of the material and the element of zeolite were studied by scanning electron microscope (SEM JEOL JSM-6610) equipped with an energy dispersive X-ray (EDAX) spectrophotometer operated at 20 kV. To monitor the formation of carbonates in cement, the samples were scanned with FTIR (The Fourier Transform Infrared Spectroscopy).

Table 1. Mortar proportions used for a specimen preparation.

Materials	0%	10%	20%	30%
Cement (kg)	0.164	0.164	0.164	0.164
M-sand (kg)	0.492	0.4428	0.3936	0.3444
Zeolite (kg)	-	0.0492	0.0984	0.1476
Water (lt)	0.082	0.082	0.082	0.082

Carbon sequestration study

Carbon sequestration study was carried out on the zeolite concrete specimens. Carbonation chamber is suitable for testing the carbon

Figure 3. Colour and texture of zeolite.

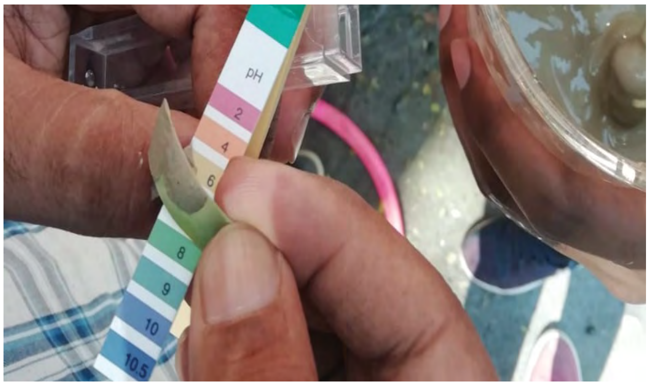


Figure 4. pH value indicated in pH strip.

Figure 5. Temperature measured using probemeter.

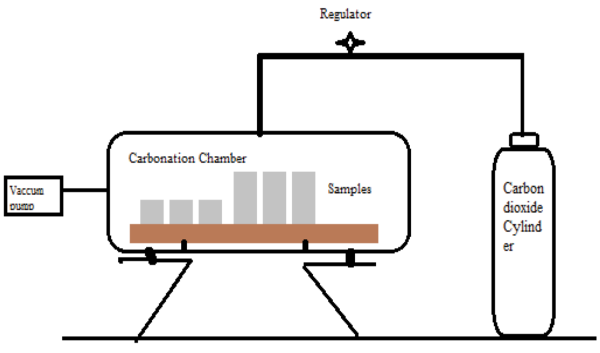


Figure 6. Carbonation chamber model.

sequestration in concrete or building materials under an environment of constant temperature, humidity and CO_2 concentration as per ISO 1920-12:2015. The zeolite concrete specimens were placed inside the carbonation chamber as shown in Figure 6. The carbonation chamber was vacuumed at – 0.5 bar with the vacuum pump, then the Carbondioxide is filled in the chamber. The pressure in the chamber was controlled at 5.0 bar with the regulator such that the flow rate of the gas was controlled by 1 to 10 l/min for 48 hours.

Carbonation reaction takes place the as the carbon dioxide intrude into the pore water and forms the weak carbonic acid which in turn reacts with the calcium hydroxide and forms the calcium carbonate and water. The carbonation reaction is indicated in Equation 1.

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad \text{---------------- 1 (a)}$$

$$Ca\,(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O \qquad \text{---------------- 1 (b)}$$

The carbonation test was performed on the carbonated zeolite concrete cube samples with phenolphthalein solution to indicate the change of pH level in the concrete. Phenolphthalein an indicator is dissolved in a suitable solvent such as isopropyl alcohol (isopropanol) in a 1% solution. The phenolphthalein solution is sprayed over the concrete as per IS 516. The depth of carbonation was determined on the zeolite concrete.

Results and Discussion

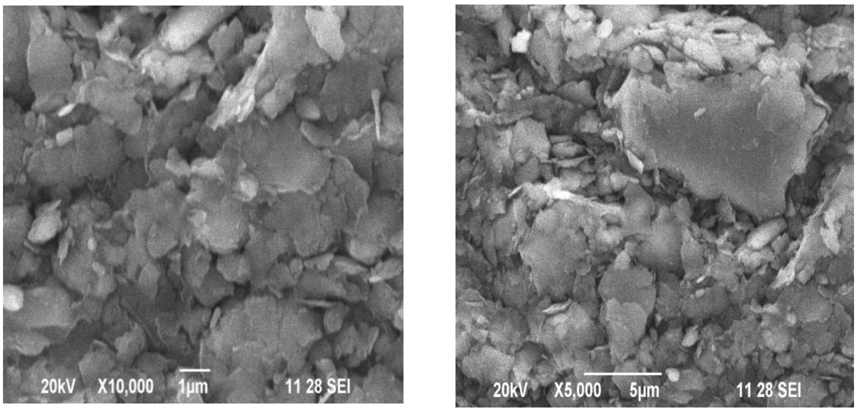
Microstructure and elemental study

The microstructure study and the porosity study of the zeolite structure was studied by Scanning Electron Microscope (SEM) as shown in Figure 7. The scanning electron microscope (SEM) image of the zeolite shows the morphology and the surface image of the zeolite. High specific surface area with high pore volume appears as the main factor for CO_2 adsorption [22]. The surface image of zeolite shows the scale formation with more porosity/voids that can trap more CO_2 into it. The EDAX pattern obtained on the zeolite material is presented in Figure 8. The elemental composition data obtained on zeolite materials is presented in Table 2.

From Table 2, the oxygen content is higher than the other elements in the zeolite. For the carbon sequestration, the presence of oxygen in zeolite indicated that the zeolite can be used for the carbon absorption [22]. The porous nature of the zeolite was also observed with the water absorption test. The moisture content for the zeolite aggregate was arrived by the oven dry method as per the IS 1270- Part 2. The average water absorption was found to be 10.02%, hence the zeolite can be replaced with the M-sand aggregate in cement mortar and in concrete.

Compressive strength of cement mortar

The compressive strength of the cement mortar and concrete were tested on cube specimens on compression testing machine of capacity 100 Tonnes. The maximum load resisted by the specimen was recorded. The compressive strength of the zeolite mortar was carried out with 1:3 cement mortar mix with partial replacement of M-sand with zeolite as 0%, 10%, 20% and 30%. The zeolite mortar were prepared with 70.06 × 70.06 × 70.06 mm cube and cured, indicated in Figure 9.



(a) (b)

Figure 7. Scanning Electron Microscope (SEM) surface image of zeolite with magnification. (a) 10000x and (b). 5000x SEM view of zeolite in different focus.

Table 2. Composition of elements in zeolite.

Elements	O	Mg	Al	Si	Ca	Fe
Atomic weight (%)	72.60	7.52	2.47	12.82	3.98	0.61

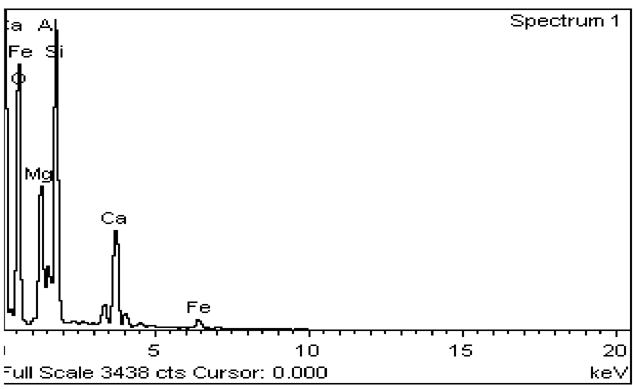


Figure 8. Composition of elements in zeolite.

Figure 9. Cement mortar cube specimen.

Table 3. Average compressive strength of 1:3 zeolite mortar.

S. No.	Percentage of zeolite replaced with M-sand	7th day strength(N/mm²)	14th day strength(N/mm²)	28th day strength(N/mm²)
1	0	3.00	9.1	10.6
2	10	3.50	10.20	11.02
3	20	3.50	10	11.63
4	30	3.00	8.7	11.22

Table 4. Compressive strength of carbonated zeolite concrete.

Percentage of zeolite replaced with M-sand	Compressive strength (in N/mm²)	
	Non-carbonated zeolite concrete	Carbonated zeolite concrete
0	15.7	15.5
25	15.48	15.31
50	15.09	15.17

The compressive strength results of cement mortar cubes were arrived at 7th day, 14th day and 28th day for specimens without and with Zeolite were indicated in Table 3.

From Table 3, the zeolite with 10% replaced with M-sand indicated that, with the increase in the zeolite content, the 28 days compressive strength was increased upto 10%, 20% and 30% increased the compressive strength by 3.96%, 9.71% and 5.85% respectively. Pozzolanic activity has influenced the ultimate compressive strength, permeability and chemical durability [23].

Carbonation test

The carbonation test was performed on 18 cubes of standard size 150 × 150 × 150 mm cast with 0%, 25% and 50% replacement of M – sand with zeolite. It was cured for 28 days then it was placed in the vacuum chamber which is a rigid enclosure from which air and other gases are removed by a vacuum pump. This result in a low-pressure environment within the chamber commonly referred to as vacuum. The vacuum environment have multiple ports, covered with vacuum flanges, to allow instruments or windows to be installed in the walls of the chamber and the specimens were placed in the chamber as shown in Figure 10. In low to medium-vacuum applications, the walls were sealed with elastomer as indicated in Figure 11.

After exposure, carbonation tests on the zeolite concrete were carried out with the phenolphthalein indicator solution sprayed on the surface in order to determine the carbonation depth. The attack of the CO_2 on the cement concrete reduces the alkalinity in the concrete. The concrete porosity allows the CO_2 to react with the alkalis like calcium, sodium and potassium hydroxides which are formed due to cement hydration in concrete. As the concrete changes its grey colour to pink, indicates that the concrete is in good condition and as there is no change in colour of concrete, indicates that the area is affected by carbonation. The reaction produces the carbonates which reduce the pH level of concrete from 13 to 9. The uncarbonated concrete is indicated in pink as shown in Figure 12.

After continuous carbonation on zeolite concrete, the carbonated depth of the zeolite concrete was measured in millimetres from the external surface at 4 to 8 positions. The control mix concrete (0% zeolite) was uncarbonated at the surface. The rate of penetration of carbonation in zeolite concrete with 25% and 50% zeolite was observed as 5 mm from the surface for every 48 hours. The incorporation of zeolite increases the level of carbon sequestration.

Compressive strength of carbonated concrete

The compressive strength of the carbonated zeolite concrete were tested and compared with the uncarbonated zeolite concrete for its strength. The average strength of the carbonated zeolite concrete and uncarbonated zeolite concrete was given in Table 4.

Figure 10. Concrete in the chamber.

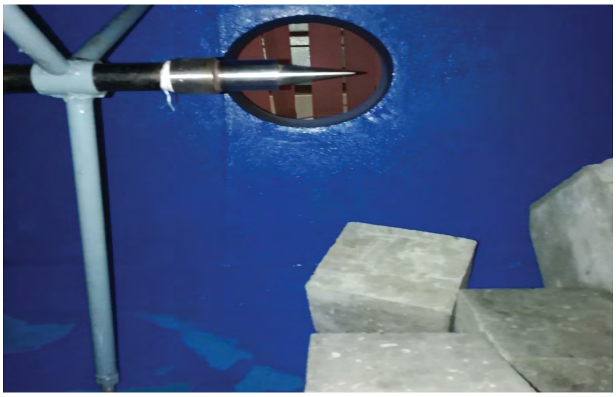


Figure 11. Vacuum chamber sealed with elastomer.

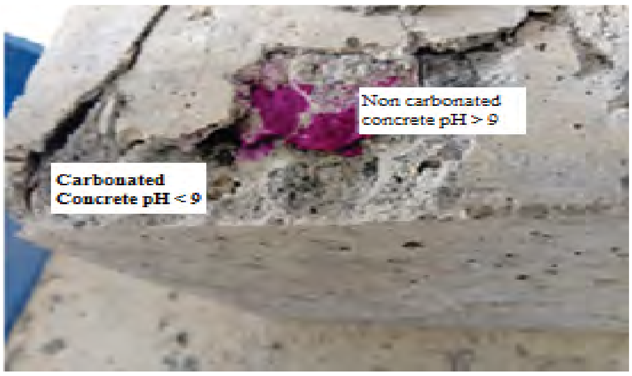


Figure 12. Degree of carbonation.

From Table 4, the strength of the carbonated zeolite concrete and the uncarbonated zeolite concrete were almost the same, which indicated that the change in the strength due to carbonation is very less. Haamhidh and

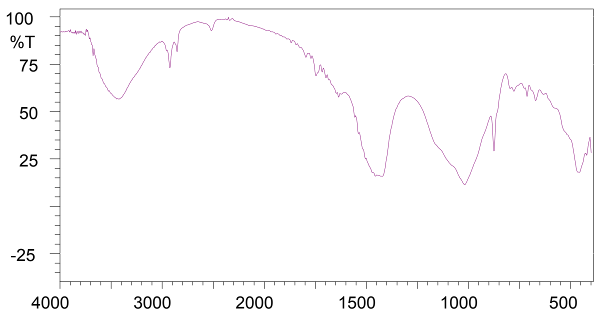


Figure 13. FTIR spectra of CO_2 absorption.

Prabavathy [24] also concluded that the compressive strength of the zeolite concrete is more or less the same compared to the cement concrete. After exposure, the concrete samples were measured for the concentration of the CO_2 absorption by IR spectrum method [25]. Fourier transformation infrared spectroscopy (FTIR) test method detects the presence of C–O in concrete samples as a basis for determining the presence of $CaCO_3$ in zeolite concrete. The FTIR spectra obtained on zeolite concrete was presented in Figure 13.

The wavelength range lies between 400 and 4,000 cm^{-1}. Generally the band presents at 3400 cm^{-1}, represent the absorption of CO_2 molecule in zeolite concrete. Figure 13 indicates that a majority of CO_2 adsorbed in the pores of the zeolite in a linear complex with the exchangeable cation, as indicated by the intense absorption band near 3444.87 cm^{-1}. Most interestingly is the formation of carbonate and bicarbonate on the external surface of zeolites as indicated by the presence of several broad absorption bands in the 1000-1500 cm^{-1} regions, suggesting unique sites for CO_2 adsorption on the surface of the zeolite concrete?

Conclusions

Based on the experimental investigations, the following conclusions were drawn;

- The water absorption of zeolite is within the permissible limits and hence it can be used in the concrete.
- The compressive strength of the 1:3 zeolite cement mortar, an average of 8.87% higher than the control cement mortar.
- The rate of carbonation depth on the zeolite concrete was 5mm for every 48 hours.
- The compressive strength of the carbonated zeolite cement concrete is almost the same as the strength of the uncarbonated zeolite control concrete.
- The incorporation of zeolite increased the level of carbon sequestration.
- Zeolite in concrete acts as the carbon sinks and can adsorb the atmospheric Carbondioxide which is a major pollutant in the atmosphere.

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