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Experimental Investigation of Biochar Additives in Geopolymer Concrete

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ABSTRACT
Cement, a vital industrial material, ranks second globally in consumption. However, its production contributes significantly to CO2 emissions, around 7% of the total. Geopolymer concrete (GPC), an innovative approach, addresses this challenge. GPC utilizes industrial byproducts, particularly fly ash, enhanced with biochar – carbon-rich material from organic sources – for improved performance and reduced environmental impact. Biochar enhances mechanical strength by fostering adhesion between concrete matrix and aggregates due to its porous and carbonaceous nature. This compact arrangement leads to elevated compressive and flexural strengths. It also curbs the alkali-silica reaction, extending GPC's structural durability. This study extensively examines biochar's role in GPC, replacing fly ash in different ratios (80G20F0BC, 80G15F5BC, 80G10F10BC, 80G5F15BC, 80G0F20BC). Alkaline activators like sodium silicate and sodium hydroxide are utilized. Concrete specimens undergo curing for 7, 14, and 28 days at room temperature. Results highlight a strong correlation between biochar content and improved mechanical properties, with a peak enhancement of 15% in fly ash replacement. Compressive, split tensile, and flexural strengths all demonstrate consistent growth. In conclusion, this study uncovers how biochar replaces fly ash in GPC, strengthening the matrix and supporting sustainable concrete production. It showcases the synergy between enhanced mechanical properties, environmental responsibility, and innovative material design.
Keywords: Carbon Dioxide Emissions, Geopolymer Concrete, Biochar, Alkali-silica Reaction, Alkaline Activators, Curing Regimen, Compressive Strength, Split Tensile Strength, Flexural Strength.

I. INTRODUCTION

In light of the aforementioned context, the present study delves into an experimental exploration of biochar's influence as a partial substitute for fly ash within GPC formulations.

The intricate interplay between biochar, fly ash, and GGBS within the GPC matrix is scrutinized for its ramifications on mechanical performance and environmental sustainability. This study not only aims to unravel the synergistic interrelationship between these constituent materials but also seeks to shed light on their pivotal role in mitigating the persistent challenges posed by the alkali-silica reaction—a factor that often undermines the durability of concrete structures. Through a meticulously devised experimental framework, involving varied alkaline activators, distinct curing regimens, and varying degrees of biochar integration, this investigation endeavours to comprehensively fathom the mechanical attributes of GPC fortified with biochar. Essential mechanical parameters encompassing compressive strength, split tensile strength, and flexural strength are assessed. This research seeks to uncover the intricate interplay of these materials, contributing to an amalgamation of advanced mechanical properties and environmental sustainability within the realm of concrete production.

The forthcoming sections elucidate the experimental methodologies, findings, and implications of this study, thereby augmenting the comprehension of biochar's potential to enhance the properties of geopolymer concrete while simultaneously addressing pressing environmental concerns.

II. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Biochar:

[1] Virgin bamboo-derived biochar, sourced from a sustainable organic farm products company, was procured with a specific gravity of 2.6. Prior to its integration into geopolymer concrete blends, meticulous assessments of its chemical composition, surface area, and pore

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structure were conducted. The biochar was derived by grinding bamboo and subsequently sieved to meet the specified size criteria (passing through a 75-micron sieve while retained on a 125-micron sieve).

2.1.1.1 Sources of Biochar

Biochar is a carbon-rich material produced from biomass through a process called pyrolysis, which involves heating organic matter in the absence of oxygen. It is used as a soil amendment to improve soil fertility, water retention, and carbon sequestration. Sources of biochar shown in Figure.2 include agricultural residues (such as crop waste), forestry residues, animal manure, and organic waste materials. The production and application of biochar can contribute to sustainable soil management and help mitigate climate change by enhancing soil health and reducing greenhouse gas emissions.

Figure.1 Biochar

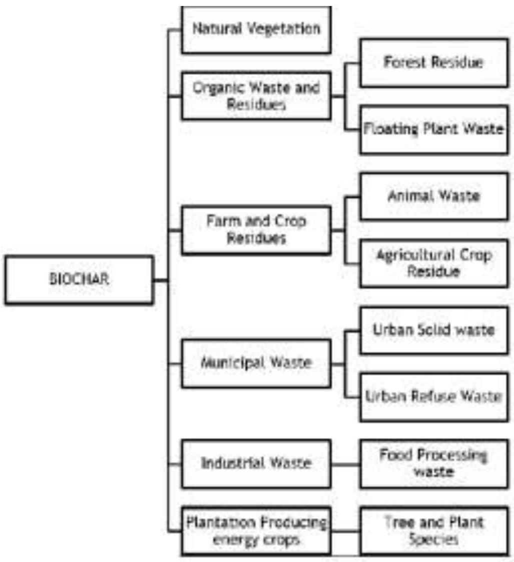

Figure.2 Sources of Biochar

2.1.1.2 SEM ANALYSIS OF BIOCHAR

SEM images of biochar in Figure.3 and Figure.4 offer a comprehensive and visually captivating view of its microstructure and surface morphology, revealing its potential significance in enhancing concrete properties.

Biochar, derived from biomass pyrolysis, exhibits a complex and porous micro-scale structure, making it an intriguing subject for SEM investigations in the context of concrete applications. The SEM images highlight a network of pores and voids of varying sizes, indicating biochar's potential as an excellent filler material in concrete mixes. Its inherent porosity provides increased surface area, which can serve as nucleation sites for cement hydration, thus enhancing interfacial bonding within the concrete matrix. Moreover, SEM images provide valuable insights into the interactions between biochar particles and the cementitious matrix, shedding light on their impact on concrete's reactivity and functional properties. Incorporating biochar into concrete offers various benefits, including improved mechanical properties, enhanced durability, and reduced carbon footprint. Its porosity enhances water retention and release, leading to better workability and decreased cracking potential in concrete.

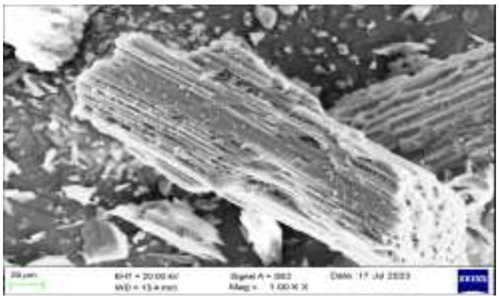

Figure.3 SEM image of Biochar

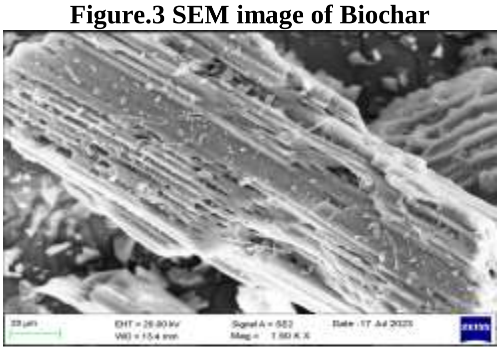

Figure.4 SEM image of Biochar

2.1.2 Fly Ash and GGBS:

Fly ash, a finely divided particulate material resulting from coal combustion in thermal power plants, constitutes the focal point of this investigation. In accordance with the stipulations set forth by the Indian standard IS 3812:2013, it is classified into two categories—Class F (low-calcium) and Class C (high calcium) fly ash. This study exclusively employs Class F fly ash, and the GGBS (Ground Granulated Blast Furnace Slag) hails from JSW.

2.1.3 Alkaline Activator Solution (AAS)

The Alkaline Activator Solution (AAS) is composed of alkali hydroxides and silicates. Sodium hydroxide emerges as the preferred alkali due to its cost-effectiveness and robust alkali nature, in contrast to potassium. The experimental procedure encompasses the amalgamation of sodium hydroxide flakes, sodium silicate solution, and water. The sodium hydroxide flakes, characterized by their white crystalline structure, exhibit a proclivity to absorb CO_2 and moisture from the atmosphere. These flakes serve to dilute the sodium hydroxide.

After the dissolution of sodium hydroxide flakes in water and a subsequent cooling phase of 24 hours, sodium silicate solution is introduced. The formulation of AAS involves employing a 12M sodium hydroxide solution and a silicate to hydroxide ratio of 2.5. Given the molecular mass of NaOH as 40, 480 grams (40×12) of NaOH pellets are combined with one liter of water to attain the 12M solution.

2.1.4 Superplasticizer:

Conplast SP430, a brown liquid grounded in Sulphonated Napthalene Polymers, exhibits rapid dispersibility in water. The composition of Conplast SP430 is meticulously tailored to confer substantial water reduction capabilities, up to 25%, without compromising workability. This facilitates the creation of high-quality, low-permeability concrete. This formulation finds pertinence within the ambit of this study.

2.1.5 Fine Aggregate and Coarse Aggregate:

The employed M-Sand conforms rigorously to the specifications outlined in IS 383:2016, ensuring its suitability for concrete production. Similarly, the coarse aggregates adhere to the standards stipulated in IS 2386:2016, thus substantiating their appropriateness for application in construction. The meticulous adherence to these established benchmarks establishes a robust foundation for the exploration and analysis of concrete characteristics and performance.

2.1 Methodology

The methodology adopted and tests conducted on the geopolymer concrete with biochar is given in Figure.A and Figure.B with which the entire work was carried out.

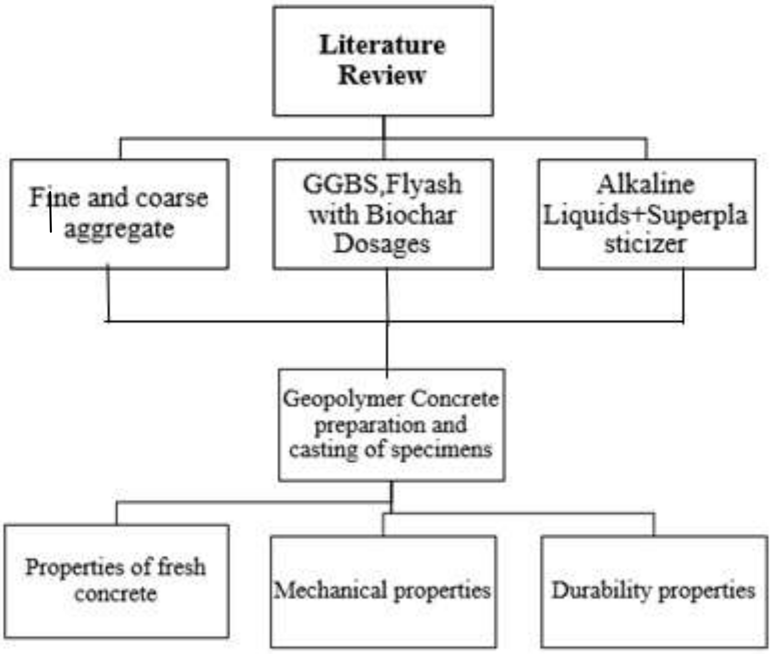

Figure.A Methodology Adopted

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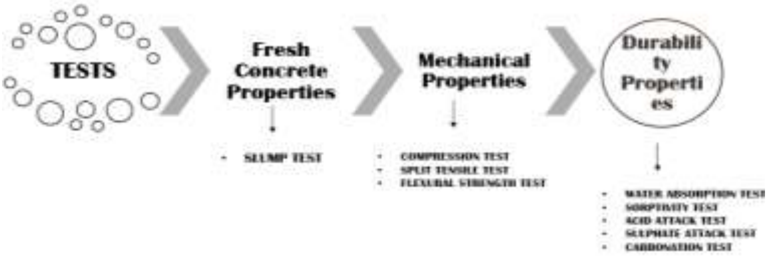

Figure.B Tests on Geopolymer Concrete

III. MIX PROPORTION:

[2] This journal study orchestrates the selection of five distinctive mix proportions, each characterized by a unique amalgamation of fly ash and biochar. Systematic manipulation of the proportions of fly ash and biochar within these mixes facilitates an investigation into their impact on the resultant material properties.

Through the meticulous selection of these mix proportions, an exhaustive analysis unveils the influence of varying ratios of these vital components on the attributes of the final product.

MIX	GGBS (%)	FLYASH (%)	BIOCHAR (%)
0	80	20	0
1	80	15	5
2	80	10	10
3	80	5	15
4	80	0	20

Table.1 Mix proportions

In geopolymer concrete, the rate of GGBS (Ground Granulated Blast Furnace Slag) shown in Table.1 replacement remains constant while adjusting the percentages of biochar and fly ash. GGBS has specific properties vital for concrete performance and is set at an optimal replacement ratio. This fixed GGBS rate establishes a consistent baseline for comparison and isolates the impact of varying biochar and fly ash content on concrete characteristics. Keeping GGBS constant simplifies optimization, aiding in achieving desired sustainability and material property goals. Moreover, standardization ensures easier comparison of results across studies and enhances reproducibility in geopolymer research and applications.

IV. SAMPLE PREPARATION

[3] The compressive strengths of all concrete mixtures (MIX 0, MIX 1, MIX 2, MIX 3, MIX4) are ascertained utilizing standardized 100X100X100 mm cube specimens, following the guidelines delineated in IS 516 (BIS 1999). Furthermore, the flexural and split tensile strengths are evaluated via a concrete bar measuring 100 mm in breadth, 100 mm in depth, and 500 mm in length. These assessments are conducted at the 28-day milestone.

[4] Within the study, Biochar (BC) is employed to replace an equal weight of fly ash across various dosages of 0%, 5%, 10%, 15%, and 20%. The binder (a/b) ratio stands at 0.45. Manual mixing techniques are employed to fabricate concrete test blocks. Aggregates and alkaline solution are manually blended using a shovel until uniform coloration is achieved. The resultant mortar mix is poured into appropriate moulds in three distinct layers, with even filling ensured by employing a flat vibrator for compaction. Following this, the concrete specimens undergo two curing conditions: room temperature curing for 7 and 28 days, and temperature curing at 60 degrees centigrade for 24 hours, with testing conducted on the 7th and 14th days.

V. TEST ON FRESH CONCRETE

5.1 Slump Cone Test:

[5] The IS 1199:2018 slump cone test is routinely conducted on geopolymer concrete to assess its workability and coherence. Fresh geopolymer concrete is filled into the slump cone in layers and allowed to settle under its weight. The reduction in height indicates the "slump." This test is crucial, especially for geopolymer concrete with biochar, as biochar's properties can affect workability. Conducting the slump cone test helps evaluate how biochar-modified geopolymer concrete flows and behaves during placement, ensuring desired construction and performance qualities. Specimens underwent assessment during the matured phase at intervals of 7, 14, and 28 days. A comprehensive analysis encompassing both destructive (DT) and non-destructive (NDT) methodologies was undertaken to scrutinize diverse attributes of engineered geopolymer mortar. The results of the test are represented in Figure.5.

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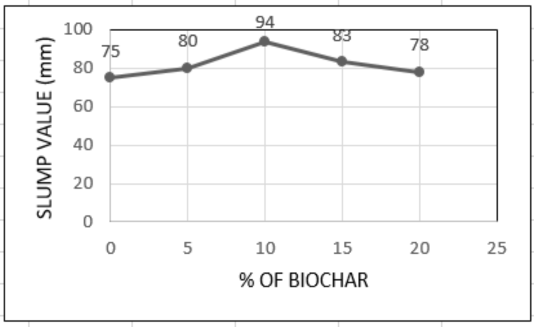

Figure.5 Slump Test

VI. TESTS ON HARDENED CONCRETE

6.1 Compressive performance evaluation

[11] In order to scrutinize the compressive strength attributes of Engineered Geopolymer Concrete (EGC) samples, the analysis involved executing tests in adherence to ASTM C-109 [52] standards. Utilizing 150 mm cube samples, the evaluation was conducted across various ages in a compression testing apparatus. Compressive strength values were determined at corresponding air curing durations of 7and 28 days. Employing a load-controlled approach, the loading rate was set at 0.25 MPa/s.

The computed compressive strength of each specimen is shown in Table.2.

MIX ID	SIZE OF CUBE (mm)	COMPRESSIVE STRENGTH N/mm2	
		7th day	28th day
80G20F0BC	150X150X150	31.68	34.52
80G15F5BC	150X150X150	32.29	35.49
80G10F10BC	150X150X150	32.98	35.87
80G5F15BC	150X150X150	33.66	37.63
80G0F20BC	150X150X150	32.21	36.25

Table.2 Compressive strength

6.2 Flexural Strength Test on Biochar-Enhanced Geopolymer Concrete

In the case of biochar-infused geopolymer concrete (GPC), flexural strength evaluation gains significance. Biochar, a carbonaceous material, introduces a unique element to GPC's microstructure. Biochar might enhance the adhesive bond between matrix and aggregates, potentially boosting flexural strength.

[12] Flexural strength assessment, or the modulus of rupture, is crucial for gauging concrete's load-bearing ability under bending forces. According to, particularly for beams and slabs.

MIX ID	SIZE OF PRISM (mm)	FLEXURAL STRENGTH N/mm2	
		7th day	28th day
80G20F0BC	500*100*100	3.1	3.8
80G15F5BC	500*100*100	3.85	4.16
80G10F10BC	500*100*100	3.98	4.23
80G5F15BC	500*100*100	4.01	4.27
80G0F20BC	500*100*100	3.2	3.74

Table.3 Flexural Strength

6.3 Split Tensile Strength Test on Biochar-Infused Geopolymer Concrete

IS code IS 516:1959, this evaluation requires applying a bending load until prismatic concrete beams with standard dimensions (500 mm x 100 mm x 100 mm) fail. This test offers key insights into structural behaviour, particularly for beams and slabs.

The split tensile strength test, guided by IS code IS 5816:1999, critically measures the tensile strength of cylindrical concrete specimens (100 mm diameter, 150 mm height) under diametral compressive forces. Compressive forces are applied until fracture occurs, revealing cohesive strength and crack resistance under tensile stresses.

[13] In biochar-enhanced geopolymer concrete (GPC), this analysis gains importance. Biochar's inclusion enhances GPC cohesion and tensile strength due to its inherent carbonaceous properties. Biochar and geopolymer interaction can foster a more robust microstructure, revealing GPC's resilience to tensile loads. The test results are shown in Table.4. This insight is crucial for applications demanding tenacity against cracks. Both flexural and split tensile strength tests with biochar in GPC introduce a new dimension. The synergy of geopolymer technology and biochar promises advanced concrete formulations, suitable alternatives for diverse construction needs.

S. NO	MIX ID	SIZE OF CYLINDER (mm)	SPLIT TENSILE STRENGTH N/mm2	
			7th day	28th day
1	80G20F0BC	100*150	3.39	4.52
2	80G15F5BC	100*150	3.78	4.79
3	80G10F10BC	100*150	4.15	4.99
4	80G5F15BC	100*150	4.38	5.13
5	80G0F20BC	100*150	4.2	4.87

Table.4 Split Tensile Strength Test

VII. DURABILITY TESTS

7.1 Water Absorption

[6] The water absorption examination was conducted following ASTM D5229 [53] protocols to quantify the water uptake within the geopolymer

International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 8 Aug 2023, pp: 410-418 www.ijaem.net ISSN: 2395-5252

matrix composite at various hardened stages. Water ingress into concrete/mortar substantially impacts durability, leading to deterioration and loss of strength. At the 28th-day milestone, specimens were subjected to 24 hours of oven drying followed by weight measurement. Subsequently, immersion in water for 48 hours ensued, and another weight measurement was taken. The absorbed moisture content was then determined by calculating the disparity between the weights of the oven-dried and fully saturated samples.

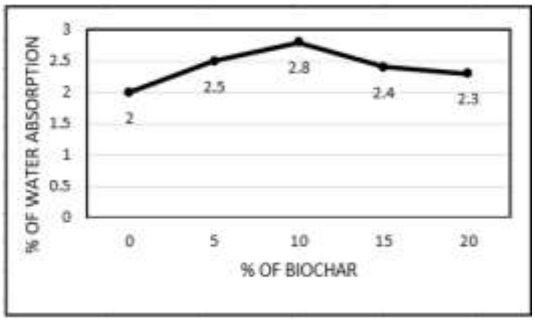

Figure.6 Water Absorption

7.2 Sorptivity Test:

[7] The sorptivity test, in accordance with IS code IS 15502:2005, serves as a pivotal assessment of concrete's absorptive capacity and capillary action potential.

It involves exposing cylindrical concrete specimens to water at one end, while tracking the ingress depth of water over time. The rate of water penetration into the concrete matrix reflects its porosity and permeability characteristics. This test aids in evaluating concrete's durability, moisture susceptibility, and resistance to potential deterioration caused by external factors.

% OF BIOCHAR	30min	60min	90min	120min
0	0.04	0.06	0.07	0.07
5	0.07	0.08	0.09	0.11
10	0.06	0.09	0.11	0.12
15	0.07	0.1	0.12	0.12
20	0.08	0.1	0.12	0.13

Table.5 Sorptivity Test

7.3 Acid Resistance Test:

[8] The acid resistance test, conforming to IS code IS 3495 (Part 1):1992, is a vital evaluation of concrete's durability against acidic environments. It entails immersing concrete specimens in acid solutions, typically sulfuric acid, and monitoring their weight loss over a specified duration. This test is instrumental in ascertaining concrete's ability to withstand chemical attacks, preserving its structural integrity and longevity in aggressive environments.

MIX ID	WEIGHT BEFORE ACID ATTACK (Kg/cum)	WEIGHT AFTER ACID ATTACK (Kg/cum)	%LOSS OF WEIGHT
80G20F0BC	2490	2483.5	0.26
80G15F5BC	2527	2522.2	0.19
80G10F10BC	2557	2553.4	0.14
80G5F15BC	2627	2624.3	0.1
80G0F20BC	2578	2573.1	0.19

Table.6 Acid Resistance Test

7.4 Sulphate Resistance Test:

[9] Conducted in accordance with IS code IS 4031 (Part 14):1989, the sulphate resistance test critically examines concrete's capacity to endure sulphate exposure.

The test involves subjecting prismatic concrete specimens to sulphate solutions and observing changes in their dimensions and weight over time. By simulating sulphate-rich conditions, this test elucidates concrete's resilience against sulphate-induced expansion and deterioration, thereby ensuring its suitability for applications in sulphate-laden environments. Test results are presented in Table.7.

MIX ID	WEIGHT BEFORE SULPHATE ATTACK	WEIGHT AFTER SULPHATE ATTACK	COMPRESSIVE STRENGTH BEFORE SULPHATE ATTACK	COMPRESSIVE STRENGTH AFTER SULPHATE ATTACK
	(Kg/cum)	(Kg/cum)	(Mpa)	(Mpa)
80G20F0BC	2468	2451.958	34.52	31.814
80G15F5BC	2506	2489.711	35.49	33.109
80G10F10BC	2538	2520.742	35.87	33.524
80G5F15BC	2616	2598.996	37.63	35.24
80G0F20BC	2562	2544.578	36.25	33.56

Table.7 Sulphate Resistance Test

7.5 Carbonation Test:

[10] Aligned with IS code IS 9013:1978, the carbonation test is a fundamental evaluation of concrete's vulnerability to carbon dioxide-induced degradation. The test entails exposing cylindrical concrete specimens to a controlled carbon dioxide-rich environment and subsequently determining the depth of carbonation penetration. This test is instrumental in gauging concrete's ability to withstand carbonation-induced reduction in alkalinity, reinforcing its durability and resistance to potential corrosion of embedded steel reinforcement. The test results are shown in Table.8.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 8 Aug 2023, pp: 410-418 www.ijaem.net ISSN: 2395-5252

MIX	DEPTH OF CARBONATION,(mm)
80G20F0BC	4
80G15F5BC	2
80G10F10BC	2
80G5F15BC	3
80G0F20BC	3

Table.8 Carbonation Test

7.6 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) examination was conducted at 28th day following the guidelines of ASTM C597 – 09 [54].

The testing apparatus encompasses a pulse-receiver unit equipped with an integrated data acquisition system, alongside two transducers. UPV measurements were executed by transmitting ultrasonic waves through the specimens. The transducers were firmly coupled to opposing ends of the samples using petroleum jelly as a coupling medium. The UPV test facilitated the determination of the pulse arrival time, signifying the duration between the application of the pulse and its arrival at the opposite facet of the specimen. The result data are given in Table.9 UPV values were derived by dividing the path length by the pulse arrival time.

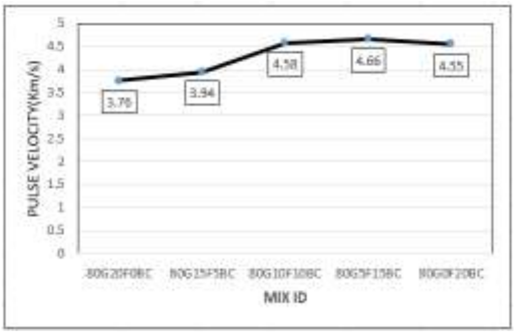

Figure.7 Ultrasonic Pulse Velocity (UPV) Test

VIII. COMPARATIVE STUDY OF ELEMENTS

8.1 SEM ANALYSIS

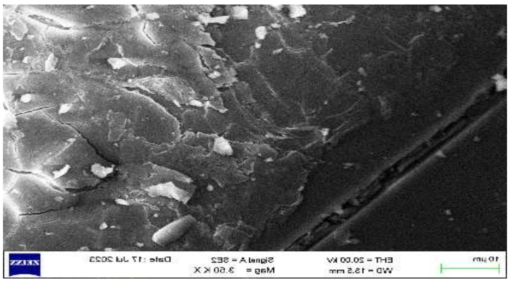

Figure.8 10% Biochar

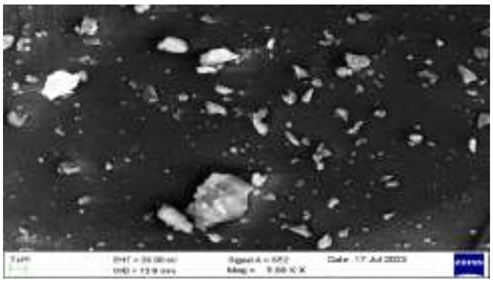

Figure.9 15% Biochar

From the SEM analysis images, comparative study of 80G10F10BC (Figure8) and 80G5F15BC (Figure.9) Cube samples were performed and from which we shall note that:

The results from the tests performed so far indicate that Mix 80G5F15BC exhibits superior performance in comparison to Mix 80G10F10BC. Notably, Mix 80G5F15BC demonstrates higher compressive and flexural strength, making it a promising option for load-bearing structures.Mix 80G5F15BC's higher GGBS and Fly Ash content contributes to enhanced pozzolanic reactivity, thereby improving strength and durability. Furthermore, the inbuilt Biochar content in both mixes enhances their environmental sustainability by sequestering carbon dioxide, promoting eco-friendly construction practices.

IX. CONCLUSIONS:

1. The sorptivity test results demonstrate that incorporating biochar into geopolymer concrete enhances its resistance to penetration up to 15% replacement of flyash by biochar, as evidenced by the reduction in sorptivity values after that when compared to nil biochar geopolymer concrete.
2. The alkalinity test assesses the pH changes. The outcomes of the test reveal that the alkaline nature of geopolymer concrete with biochar is lower in carbonation comparison to 0%biochar geopolymer concrete.
3. Acid attack test and sulphate attack test reveals very less percentage of reductions in strength that is lesser than 8 percentage.
4. UPV test results revealed shows good concrete quality where the values are above 3.5(km/s).
5. 80G5F15BC shows improved tensile strength, crucial for dynamic loads.
6. The biochar additives however, can help to protect the concrete from the acid. The biochar particles can react with HCl and form a protective layer on the surface of the concrete. This layer can help to prevent the HCl from penetrating the concrete and causing further damage.

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