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Evaluating the Microstructural and Nondestructive Characteristics of Engineered Cementitious Composites Modified with Marble Powder

John Eso [1], Oki Victor [2], Boluwade Segun [3]

[1] Department of Civil, Construction and Environmental Engineering, North Carolina State University
[2] Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure.
[3] Department of Project Management Technology, Federal University of Technology, Akure.

Abstract

Conventional cement-based mixtures are prone to micro-fracturing, which compromises structural integrity by allowing aggressive environmental fluids to penetrate the matrix. To mitigate this vulnerability, biological self-healing mechanisms offer a promising alternative to traditional repair methods. This investigation explores the integration of Bacillus subtilis microorganisms into M40 grade mixtures, utilizing both Ordinary Portland and Portland Pozzolana cements, to evaluate their impact on structural and thermal characteristics. Through the continuous biological precipitation of calcium carbonate under favorable conditions, these microorganisms effectively seal internal micro-fractures. Experimental findings indicate significant improvements in structural performance, specifically an 18% boost in compressive capacity, a 13.84% enhancement in flexural performance, and an 11.32% rise in split tensile capability for the standard mixtures compared to conventional baselines.

Additionally, the bio-enhanced specimens demonstrated improved workability and exhibited superior structural resilience with noticeably fewer fractures when subjected to elevated thermal conditions. Microstructural examination via Scanning Electron Microscopy further verified the successful internal formation of calcite crystals, validating the self-healing process.

Keywords: Engineered Cementitious Composites, marble powder, polyvinyl alcohol fibers, ultrasonic pulse velocity, microstructural analysis.

INTRODUCTION

Concrete is fundamentally the most important material utilized in modern engineering and construction projects across the globe. While this traditional material is highly valued for its exceptional compressive strength and overall density, it possesses a significant structural vulnerability in that it is inherently brittle and extremely weak when subjected to tensile stress [8]. The typical matrix of conventional concrete consists of ordinary cement, river sand, coarse aggregates, water, and various chemical admixtures designed to modify workability. The normal proportion of the material is as shown in figure 1 [5].

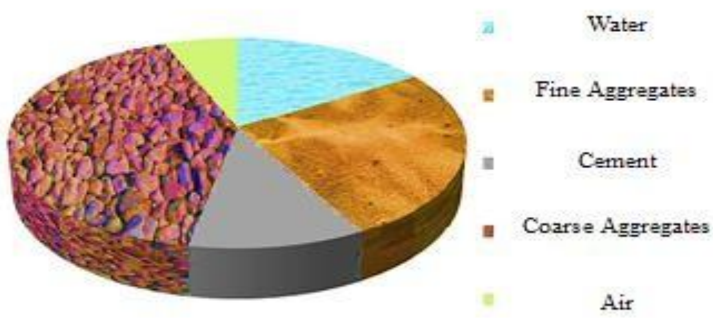

Fig 1: Typical composition of normal concrete (Source: A Khitab 2012)

However, conventional concrete has a very low strain capacity of 0.1 percent. When the stress applied to the structure exceeds this ultimate limit, microscopic cracks begin to form and rapidly propagate throughout the material. These visible cracks create pathways that allow water and deleterious chemical agents to penetrate the internal matrix. This infiltration inevitably leads to the corrosion of internal steel reinforcement and causes the eventual structural failure and severe degradation of the concrete durability [14]. To increase the durability and strength of the structure, new methods for reducing the crack width must be found out [11].

In recent years, the civil engineering community has shifted its attention toward performance-based design concepts to address these critical durability flaws. The most prominent solution developed to improve the brittle behavior of concrete is a highly ductile smart material known as Engineered Cementitious Composites. This material was originally invented by Professor Victor Li at the University of Michigan and is commonly referred to as bendable concrete. Engineered Cementitious Composites operate on a special design concept that significantly modifies the brittle nature of standard concrete by entirely eliminating coarse aggregates from the physical matrix [10]. The specialized mortar relies instead on ordinary Portland cement, silica sand, fly ash, polyvinyl alcohol fibers, and high range water reducing agents [14]. The normal ranges of Engineered Cementitious Composites are as shown in figure 2 [5].

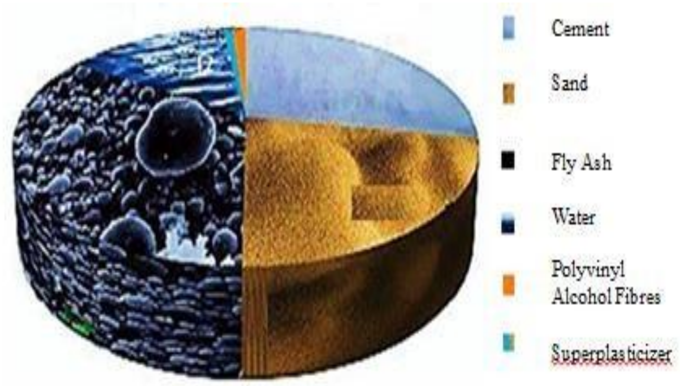

Fig 2: Typical composition of ECC (Source: A Khitab)

According to Professor Victor Li, this unique composite is approximately forty percent lighter than normal concrete and exhibits an astounding five hundred times more resistance to cracking. The remarkable flexibility of this material is derived from the presence of short, discontinuous polyvinyl alcohol fibers that absorb and distribute flexible stresses. Recent advancements in sustainable materials engineering further support this structural approach, demonstrating that incorporating alternative and waste fibers into concrete matrices significantly improves both structural strength and overall durability [16]. Furthermore, broader investigations into alternative concrete reinforcements have highlighted the critical need for improving the flexural characteristics of specialized concrete beams to prevent catastrophic failure under load [17]. Building on these proven principles of fiber reinforcement, Engineered Cementitious Composites can achieve impressive compressive strengths ranging from 20 to 95 MPa alongside flexural strengths between 10 to 30 MPa [7].

The present research introduces an innovative modification to the standard engineered composite matrix by incorporating marble powder as a partial replacement binder for ordinary Portland cement. Marble powder is a metamorphic rock byproduct generated during the sawing and shaping of pure limestone marble. This experimental study systematically examines composites containing different levels of marble powder, specifically replacing the cement component at intervals of 5 percent, 10 percent, 15 percent, and 20 percent. The primary objectives of this investigation are to evaluate the compressive strength of the matrix using nondestructive ultrasonic testing and to thoroughly analyze both the chemical composition and the microstructural transformations resulting from the addition of marble powder [9]. The various nondestructive tests on cubes and matrix powder were conducted in the laboratory as per the flowchart shown in figure 3.

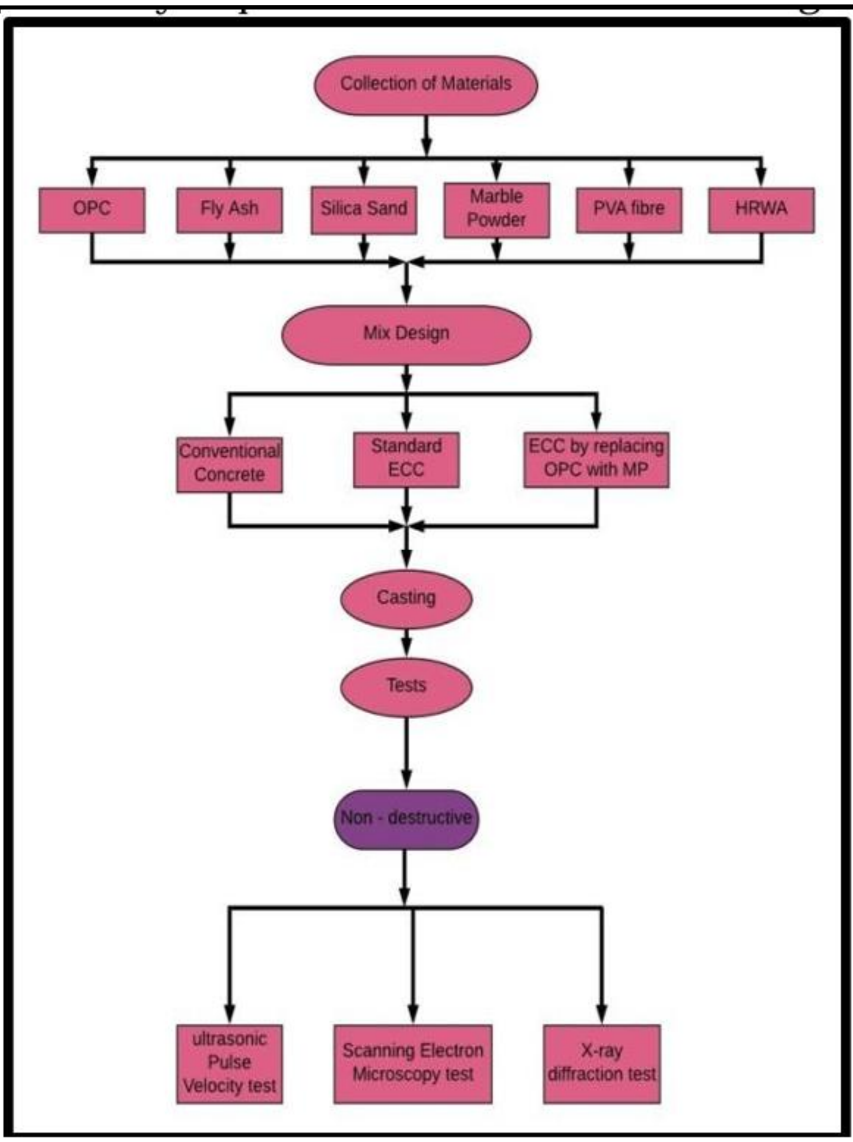

Fig 3: Methodology of Preparing Engineered Cementitious

METHODOLOGY

Materials and Mix Proportions

The cementitious matrix developed for this research utilized 53 grade Ordinary Portland Cement Type I, which complies with IS 269 2015 standards and features a Blaine surface area of 297 square meters per kilogram. The mix also incorporated Class F Fly Ash with a specific gravity of 2.33 and a Blaine fineness of 378 square meters per kilogram. Instead of standard river sand, which typically ranges from 0.0625 millimeters to 2 millimeters in diameter, the researchers utilized specialized silica sand containing 80 to 90 percent silica polymers to form the dense mortar. The crucial ductile properties were provided by light yellow Polyvinyl Alcohol fibers. These specialized fibers measure 6 millimeters in length and possess a high tensile strength greater than or equal to 6 cn per dtex. The Polyvinyl Alcohol fibers are distinctively coated with a slick substance that allows the individual fibers to slip slightly when overloaded rather than fracturing immediately. This controlled slipping mechanism is the primary factor that prevents catastrophic crack propagation within the structure. The experimental marble powder utilized in the matrix exhibited a specific gravity of 3.15 and a Blaine fineness of 306 square meters per kilogram. The physical and chemical characteristics of fly ash and marble powder are presented in Table 1.

Table 1. Chemical Characteristics of Fly ash and Marble Powder

Parameters	Chemical Characteristics (%)						Physical properties	
	SiO_2	MgO	SO_3	Na_2O	LOI	SiO2 + Al2O3 + Fe_2O_3	SG	BF
FA	46.32	1.34	0.74	0.44	2.8	87.84	2.33	378
MP	0.05	1.7	1.2	1.4	2.9	76.9	3.15	306
Note: BF= Blaine Fineness (m^2/kg), LOI= Loss on ignition, SG= Specific gravity								

Finally, Sika Viscocrete 5201 NS was employed as the high range water reducing agent to maintain the necessary flowability of the mixture. Prior to formulating the experimental batches, the pozzolanic activity index of the marble powder was rigorously evaluated according to ASTM C311 testing standards. A test mixture was created by replacing 20 percent of the standard cement with marble powder, and its compressive strength was compared against a control mixture after a 28-day water curing period. The control mixture achieved an average compressive strength of 41.96 MPa, while the test mixture reached 39.27 MPa. This resulted in a calculated strength activity index of 92.75 percent. Because this value significantly exceeds the 75 percent minimum requirement established by ASTM C 311, the marble powder was officially validated as a highly effective pozzolanic material suitable for high performance engineering applications. Following this validation, the researchers prepared five distinct composite mixtures utilizing a consistent water to cement ratio of 0.3. The reference mixture contained zero marble powder, while the four experimental mixtures systemically replaced the ordinary Portland cement with marble powder at mass percentages of 5, 10, 15, and 20. The exact proportions are summarized in Table 2.

Table 2. Mix Proportions of ECC

Mixture Proportions	Mix Proportions (Kg/m^3)				
	*ECC 0%	ECC 5%	ECC 10%	ECC 15%	ECC 20%
Ordinary Portland Cement	703	656	609	563	516
Fly Ash	234	234	234	234	234
Marble Powder	-	46.88	93.75	140.63	187.50
Silica Sand	932	925	918	911	905
PVA	0.94	0.94	0.94	0.94	0.94
HRWA	2.81	2.81	2.81	2.81	2.81
Water	300	300	300	300	300

The researchers noted that higher replacement levels of marble powder introduced significant difficulties in achieving a uniform distribution of the Polyvinyl Alcohol fibers throughout the mixer. To mitigate this negative clumping effect, the volume of the high range water reducing agent was proportionally increased in tandem with the higher marble powder replacement levels.

Preparation of Specimens and Testing

The physical specimens were cast utilizing a standard concrete mixer and placed into molds. The researchers produced cubic specimens measuring 150 millimeters by 150 millimeters to assess compressive strength. All cast specimens were maintained inside their respective molds at normal ambient temperatures for an initial period of 24 hours. Following this initial setting phase, the molds were removed, and the concrete specimens were fully submerged in a laboratory water curing medium for required durations of 7 days and 28 days.

RESULTS

Compressive Strength Evaluation

The structural quality and compressive strength of the cured concrete specimens were evaluated utilizing the Ultrasonic Pulse Velocity nondestructive testing method in accordance with IS 13311 Part 1 1992. Figure 4 shows the experimental setup to perform an ultrasonic pulse velocity test.

Fig 4: Experimental setup to perform ultrasonic pulse velocity test (Actual photograph of the setup)

This advanced technique involves transmitting a distinct ray of ultrasonic pulses entirely through the concrete cube and carefully measuring the total time required for the wave to travel across the established distance. The velocity of the transmitted pulse serves as a direct indicator of internal quality. A higher measured velocity confirms that the concrete matrix is dense and structurally sound, whereas a lower velocity indicates poor quality characterized by internal voids and extensive micro cracking. Table 3 indicates the quality of concrete based on velocity.

Table 3: Results of UPV

S/No	Member	Distance (mm)	Time (micro sec)	Velocity (Km/sec)
1	Concrete Cube	150	35.40	4.24
2	Concrete Cube	150	34.90	4.30
3	Concrete Cube	150	34.90	4.30

The experimental testing revealed that the ultrasonic pulse velocities for the marble powder modified concrete cubes consistently ranged between 4.24 kilometers per second and 4.30 kilometers per second, with an average transit time of approximately 34.90 to 35.40 microseconds across 150 millimeters. Because these recorded velocities fall firmly within the optimal quality range of 3.5 to 4.5 kilometers per second, the data conclusively indicates that the engineered concrete is of excellent quality and is entirely suitable for demanding construction purposes.

Microstructural Examination

The researchers conducted a highly detailed microstructural evaluation of the crushed and sieved concrete powder utilizing a Philips XL 30 Scanning Electron Microscope. The imaging process employed significant spot magnifications ranging from 5.00 KX up to 50.00 KX to accurately capture the internal topography of the composite. The spot magnification was carried out on the sample, which can be seen in Figure 5.

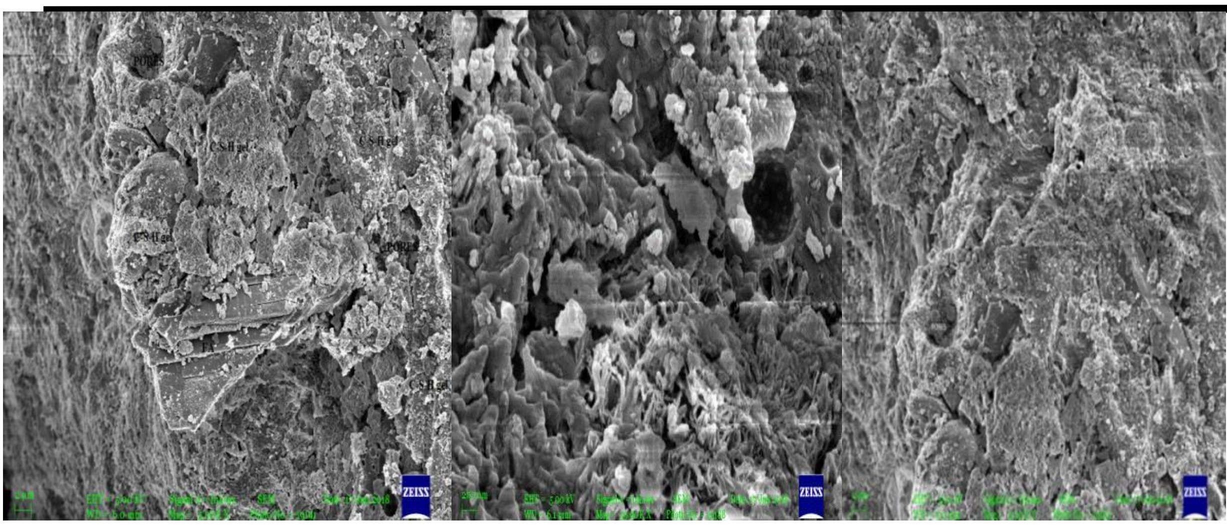

Fig 5: Microstructure and self-healing of the sample after 28 days curing comprising of (a), (b), (c) of SEM

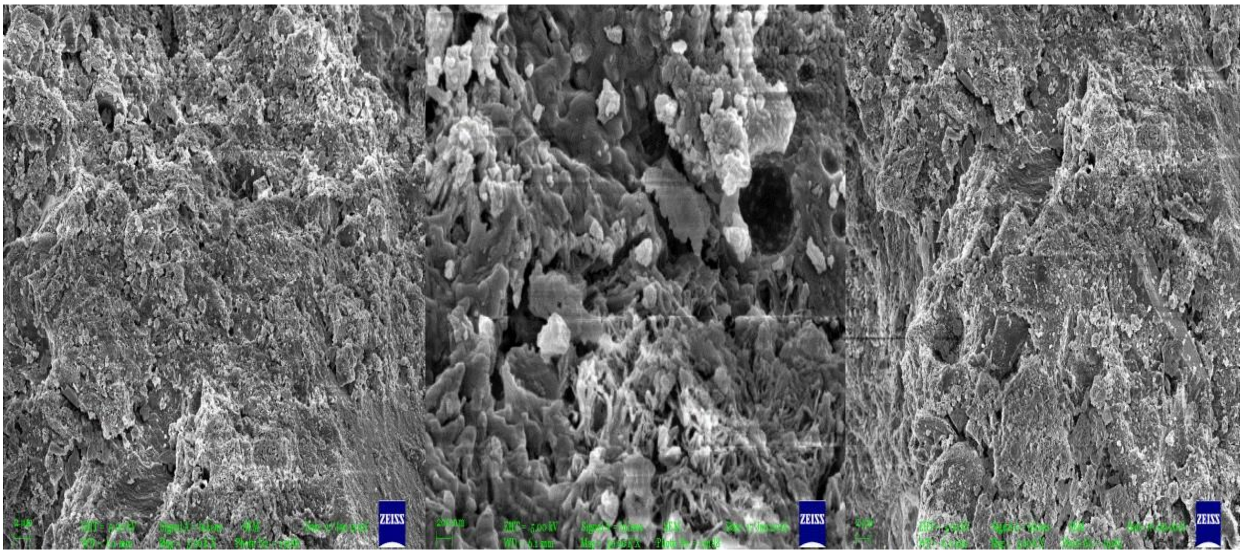

Fig 6: Microstructure and self-healing of the sample after 28 days curing comprising of (d), (e), (f) of SEM

The resulting high-resolution micrographs revealed a highly complex matrix characterized by pores of widely varying sizes distributed across different crust formations. The most crucial observation from the scanning electron microscope testing was the prominent discovery of Calcium Silicate Hydrate gel. This vital reaction product was found continuously deposited across the surface of the matrix, fundamentally contributing to the enhanced strength of the bendable concrete. Furthermore, the imaging identified dense deposits of Calcium Hydroxide resulting from the extensive chemical reactions. The distinct presence of these specific reaction products visibly interacting within the matrix actively supports the self-healing mechanisms associated with the polyvinyl alcohol fibers and the marble powder supplementation.

Investigation of Chemical Compounds

To precisely identify the specific chemical phase changes occurring within the matrix due to the addition of marble powder and silica sand, the researchers performed X ray diffraction analysis using a sophisticated Philips X pert pro pan analytical system. The powdered concrete sample was carefully mounted onto a holder and smoothed with a glass slide to ensure a perfectly uniform scanning surface. The specimen was then placed inside a diffractometer and scanned continuously at a constant rate from 40 to 90 degrees. The graph was formed on the system attached to the machine, as shown in Figure 7, and further analyzed.

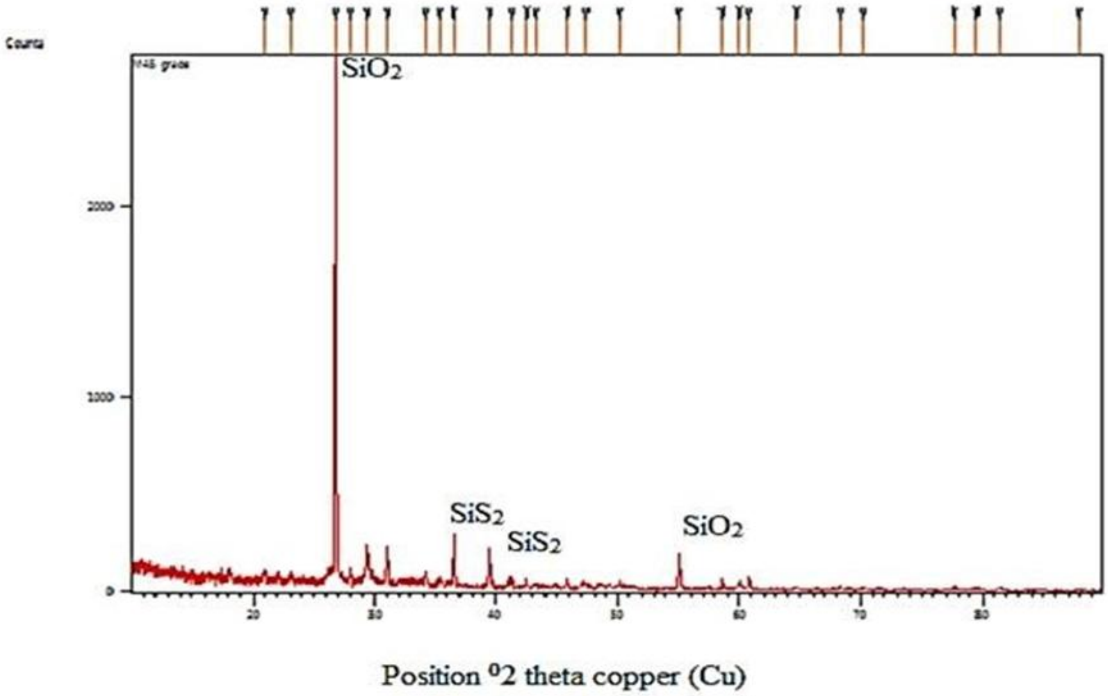

Fig 7: XRD Analysis

The resulting graphical analysis highlighted a massive and distinct peak located perfectly at the 27-degree position on the 2-theta copper scale. This major peak explicitly confirms the heavy presence of Silicon Dioxide within the concrete framework. Additionally, the X ray diffraction process successfully detected multiple smaller peaks near the 36.57 and 39.51 positions. These secondary measurements securely indicate the successful formation of Silicon Disulfide during the curing process, completely verifying the active chemical integration of the experimental pozzolanic materials.

CONCLUSION

The comprehensive laboratory testing and subsequent analysis of Engineered Cementitious Composites modified with marble powder yielded several definitive findings regarding the structural viability of the material.

First, the internal velocity of the concrete measured by the ultrasonic pulse velocity test consistently demonstrated values between 3.50 and 4.5 kilometers per second. These specific high velocity readings definitively prove that the overall structural quality of the modified concrete is excellent and structurally sound.

Second, both the scanning electron microscope imaging and the X ray diffraction chemical profiles clearly indicate that the combined effect of marble powder and polyvinyl alcohol fibers effectively facilitates the autogenous self-healing of internal cracks within the concrete matrix.

Third, the high magnification spot testing conducted during the scanning electron microscope evaluation revealed a complex internal structure featuring heavily distributed pores of varying sizes. This specific porous topography is an essential characteristic that allows the composite material to flex safely under severe strain.

Finally, the microstructural evaluation definitively confirmed the robust and continuous surface deposition of calcium silicate hydrate. This critical hydration product acts as the fundamental chemical binder that provides the advanced composite with its exceptional durability and its impressive resistance to structural failure.

Conflicts of Interest: All authors declare that they have no conflict of interest associated with this research work. **Funding:** No special funding was received for this research work.

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