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# Exploring the Synergy of High Performance Composite Concrete Strength and Sustainable Construction Practice

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**_Abstract_**

*This research evaluates how the combination of industrial waste materials optimizes composite concrete structure strength and services the interests of sustainable construction development. This research examines two major environmental problems stemming from ordinary Portland cement clinker manufacturing and landfill accumulation of non-biodegradable porcelain waste. The research employed alccofine dosage of 16% as a supplementary cementitious material (SCM) with high pozzolanic activity to combat these problems. Processed porcelain waste aggregates filled the gap in natural coarse aggregates by substituting 1% to 5% of the total volume. The mechanical properties of mixed concrete along with compressive strength and microstructural examination through SEM and XRD analysis of the produced composite concrete materials. Testing shows that alccofine's pozzolanic actions combine effectively with the enhanced packing arrangement stemming from PWAs. The composite mixture produced the best results with 16% alccofine and 3% PWA since it reached 44.15 MPa in 28 days and 54.02 MPa in 90 days surpassing both the control mix and other compositions. This research outcome demonstrates the ability of this combination to produce environmentally safe composite concrete while decreasing its embodied carbon content. The research establishes the practical use of industrial waste materials for environmental sustenance and modern construction requirements fulfillment. The obtained results advocate for using sustainable measures that conform to circular economy practices to minimize the environmental footprint of construction activities.*

**Keywords:** Alccofine (AL), porcelain waste aggregate (PWA), sustainability, supplementary cementitious material (SCM), high performance composite concrete (HPCC)

## INTRODUCTION

The construction sector has contributed significantly to global carbon emissions, primarily through the widespread use of cement in concrete production. Cement manufacturing processes alone account for almost 8% of worldwide atmospheric carbon release, forming it one of the most environmentally friendly industrial activities [1]. Industry trust in natural resources, particularly in assemblies, has led to important environmental degradation such as design, fatigue in natural stone reserves, and excessive energy consumption. Sustainable alternatives that mitigate these environmental problems are urgently needed, while simultaneously maintaining or improving the mechanical performance of concrete structures [2]. SCMS Ultra-Fine Palm Oil Fuel Ash (UFPOFA) emerges as a supplementary cementitious material (SCM) from the power plant combustion of palm waste materials including palm core shells and palm fibers.

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When mixed with water UPOFA produces cement-like compounds including calcium silica hydrate (C-S-H) while the silica ($SiO_2$), aluminum oxide ($Al_2O_3$) and iron oxide ($Fe_2O_3$) in UPOFA react with calcium hydroxide ($Ca(OH)_2$) in the solution. Using UPOFA in concrete formation leads to enhanced concrete durability alongside improved strength properties [3]. The thermal plants generate Waste Bed Ash (WBA) through coal combustion operation which they extract from their oven bottoms. The substance consists of silica alongside aluminum oxide and iron oxide and calcium oxide (CAO) along with trace elements. Addition of WBA in concrete works to lower cement requirements while presenting both environmental and sustainability advantages [4]. The calculated sound is produced by heating the sound of the kaolinite at a temperature between 600°C and 800°C. This process is known as calcination, converts sound into a reactive pozzolanic material. The main mineral of kaolinite tone is kaolinite ($Al_2Si_2O_5(OH)_4$) which becomes metakaolin ($Al_2Si_2O_7$) in cold weather. Rice shell ash (RHA) comes from the burning of rice shell ash, the outer shells of rice grains. RHA is by-Product of the rice grinding process and is considered an environmentally friendly material due to its pazzolanic properties. When used on high surfaces up to 50m²/g, the low implant density (0.2°C/cm) improves concrete strength and durability [5-6]. Metakaolin produces a calcination of kaolin at temperature from 650°C and 800°C, removing chemically bound water, and the material is converted to amorphous, highly reactive alumino-silicate. It enhances pressure and bending strength by forming additional silicic liquor calcium (C-S-H) [7]. Flag ash (FA) from the production of coal combustion in thermoelectric power plants. Class F flight ash comes from burned anthracite or bituminous charcoal, with low calcium content (<10%) and improved durability and resistance to chemical attacks. Class C flight pockets made of burning lignite or subbituminous charcoal and high calcium content (over 20%) can hydrate themselves and contribute to early strength [8]. Limestone powder (LP) is finely ground calcium carbonate (COCO3), which is usually added to portal vein cement or mixed cement. Replacing a portion of the clinker with LP reduces CO emissions from cement production. Usually between 5% and 15%, depending on the weight of the cement [9]. When mixed with calcium hydroxide from cement hydration and water the floor-grained furnace slag (GGB) produces cement-like compounds through their reaction. The material contains 20% 70% of Portland cement alongside varied exchange levels. The material prevents thermal cracking as well as defends against sulfate attack, alkali-silica reaction (ASR) and chloride penetration. [10]. Glass powder (GP) particle size (<45µm) is excellent in its reactive and cementitious properties. Contains amorphous silica (SIO). It reacts to cement calcium hydroxide $Ca(OH)_2$ to create additional filamentous calcium (C-S-H). Biomedical waste (BWA) is derived from the controlled combustion of biomedical waste, similar to traditional lethal materials such as flight ash [11-12]. Waste ash (WWA) is born from the combustion of wood in an industry, power plant, or biomass system and also contains potassium oxide ($K_2O$), magnesium oxide (MgO), and iron oxide (Fe2O3). The fine particles improve responsibility and strength [13]. E-waste, made of glass, plastic and metal in particular, can be treated and recorded with cement materials to improve performance and reduce environmental impact. Glass recovered from electrical waste such as cathode beam tubes (CRTSs) and LCD screens can be grounded to fine powder and used as pazzolanic material [14]. These materials often come from industrial and factory waste and, if not implemented, contribute to the deterioration of ecosystems and health risks. By treating these wastes, they can be used effectively in the construction industry as SCMs. The incorporation of industry by industry materials at partial ratios shows promise as cement and aggregate replacements. Reuse of these materials in concrete production not only reduces pollution, but also contributes to initiatives to maintain resources and the circular economy. Alccofine complementary cement material (SCMS), alccofine has attracted considerable attention due to its ultrafine particle size and excellent tumor properties [15]. By improving the pore structure, alccofine improves durability and concrete mechanical properties, increasing initial strength and improvement in resistance to chloride and sulfate attacks. Various studies have reported that alccofine involvement improves responsibility, reduces permeability, and improves the long-term mechanical properties of composite concrete [16]. Alccofine facilitates enhanced connection between cement paste and aggregate through improved interfacial transition zone (ITZ). It reduces porosity and contributes to superior mechanical performance over time [17, 18]. It has been found that it is also a sustainable construction practice. Such materials are porcelain waste units (PWAs) derived from discarded tiles, sanitary products and other ceramic products. Porcelain waste is not biodegradable and sets a considerable environmental problem in landfills [19]. The tensile strength of alkali treated 5 wt% areca fiber (AF) (20 wt%)/ glass fibers (GF) (20 wt%) came up to maximum tensile strength of 62.6 percent compared to untreated fiber with least percentage wt of only 10 wt. [20]. The extracted as-received fibers, which were obtained as technical fibers with a diameter of 100 to 150 w, had the density of 1200 $kg/m^3$ [21]. The roughness of the fibers was within range of the roughness of other natural fibers like itself and can be termed as silky based on their values of the kurtois [22]. Both SEM and AFM measurement of surface roughness indicated that this bit of fiber had the fewest roughness in FRL aerial root [23]. The epoxy was sufficient to shield the bark fibers and the composite resinated at the same temperature could resist degradation as nearly as resin, with little structural damage up to 320 o C [24]. The fibers barely had 4% and perhaps this is a very typical amount of this type of fibers due to the tendency to fibrillation. This will somehow compare these composites to ones having similar quantity and length of natural fibers [25]. the presence of these hybrids, to wear-resisting applications, in high-moisture conditions, and the even lesser water absorption then which are provided through addition of banana fibers to kenaf fibers [26]. With high strength, low moisture absorption and stable chemical composition, PWA has demonstrated its potential as a suitable alternative to natural units in concrete production. Research shows that replacing natural units with PWAs can improve wear resistance, reduce density and improve durability performance [27, 28]. The research evaluates concrete mechanical properties under pressure tolerance using 16% alccofine substituted cement while replacing part of the fine bone aggregates at various PWA proportions (1% to 5%). The research objective is to find suitable PWA percentages which enhance concrete performance while helping achieve sustainability targets. The results are expected to promote the creation of eco-friendly building materials, reducing carbon emissions and effective use of the industry through production in the construction sector.

## PROBLEM DEFINITION

Typical portland cement serves as a primary ingredient of nominal concrete enabling the formation of hard concrete properties. Cement production has contributed significantly to pollution, and researchers have started to look at alternative pazzolanic materials. These materials are intended to eliminate contamination concerns while simultaneously maintaining or improving the mechanical and permanent properties of concrete. Several studies analyzed the inclusion of metakaolin and fly ash materials and nano-silica in concrete mixtures to improve their performance. The purpose of this study evaluates whether alccofine can substitute cement and porcelain waste units (PWAs) as replacement materials for coarse aggregates in concrete material composition. The research goal targets the examination of mechanical HPCC behavior and environmental pollution reduction through these materials.

## OBJECTIVES

In this study, experiments were conducted to develop high performance composite concrete (HPCC) by partially placing cement in fixed alccofine (16%) and partially replacing coarse units with porcelain waste units (PWA) (1%, 2%, 4% and 5%). The study illuminates the results of mechanical property tests performed on all concrete mixtures. Key focus of this study is on assessing the effects of alccofine and PWA on the long-term durability properties and strength of initial strength in high-performance concrete. Furthermore, the research evaluates HPCC development alongside novel mechanical traits that promote sustainable construction methods.

## MATERIAL USED

### Cement

The physical properties of cement were evaluated using standardized testing procedures following the specifications described (Part 1). This standard defines the requirements for Portland Pozzolana Cement (PPC) and ensures consistency and quality in the construction of applications [31]. Various tests were performed to evaluate important physical parameters such as initial and final set times, fineness, consistency, specific gravity, and compressive strength (IS 1489-1:1991). Property characteristics of cement serve to determine concrete performance, mixtures and affect factors such as treatment, strength development, and durability. The published results of these reviews appear in Table 1.

**Alccofine**

Alccofine (AL) a finely processed SCM obtained from slag. It is known for its high glass content, improved reactivity, and reduced silica composition [29]. The Ambuja Cement Ltd. manufactured AL 1203 falls under the ASTM C989-1999 standard. The data regarding Alccofine's physical attributes and chemical properties exist in Tables 1 and 2, while in figure 1 (a) packing effect of cement particles, in Figure 1 (b) packing effect of alccofine particles and microstructural analysis through the Figure 2 shows images taken by the Scanning Electron Microscope (SEM). Additional cement material with high container activity, used for 16% replacement levels of cement.

**Porcelain Waste Aggregate (PWA)**

Crushed or recycled porcelain materials used as an aggregate substitute in concrete or other construction applications. It is part of sustainable construction practices where waste porcelain from demolished buildings, defective sanitary ware (like sinks, toilets, or tiles), or ceramic industries is repurposed instead of being discarded in landfills. A fractional replacement for coarse aggregate in concrete or construction materials is an innovative approach to address both environmental concerns and resource efficiency. By incorporating PWA derived from industrial and sanitary waste, [30,31].

**Table 1** Alccofine physical properties.

| **Physical characteristics** | **PPC** | **Alccofine** |
|---|---|---|
| Sp. Gravity | 3.15 | 2.90 |
| Sp. Surface Area | 350 [m²/kg] | 1200 [m²/kg] |
| Bulk Density | 1440 [kg/m³] | 680 [kg/m³] |
| Particle Size of Alccofine | | |
| $D_{10}$ | 02.0 | |
| $D_{50}$ | 06.0 | |
| $D_{90}$ | 09.0 | |

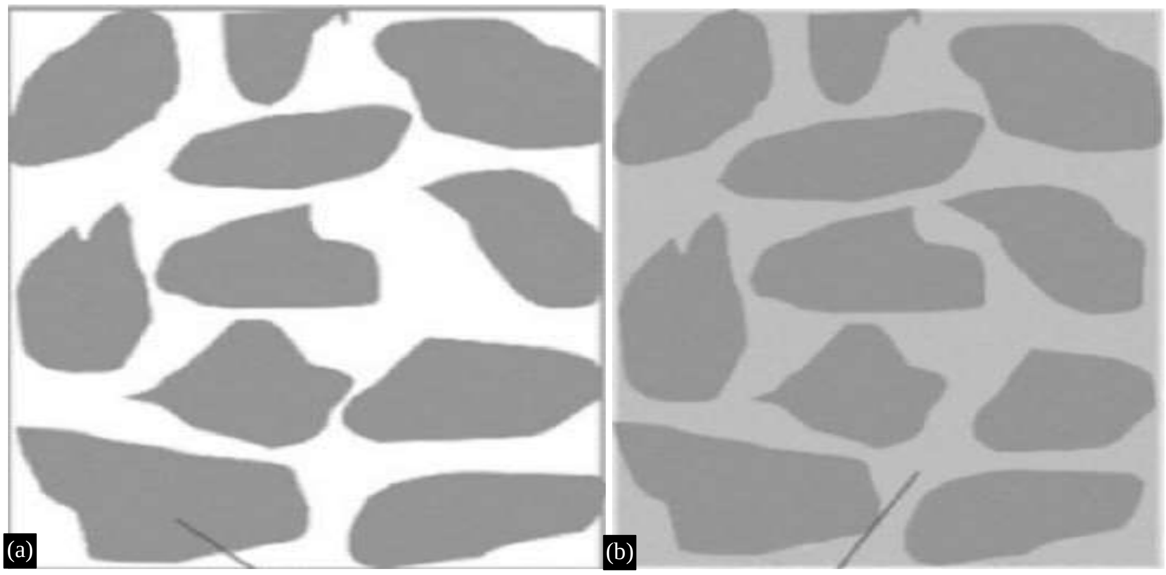


**Figure 1.** (a) & (b) represent cement particles and alcccofine ultra fine particles.

 

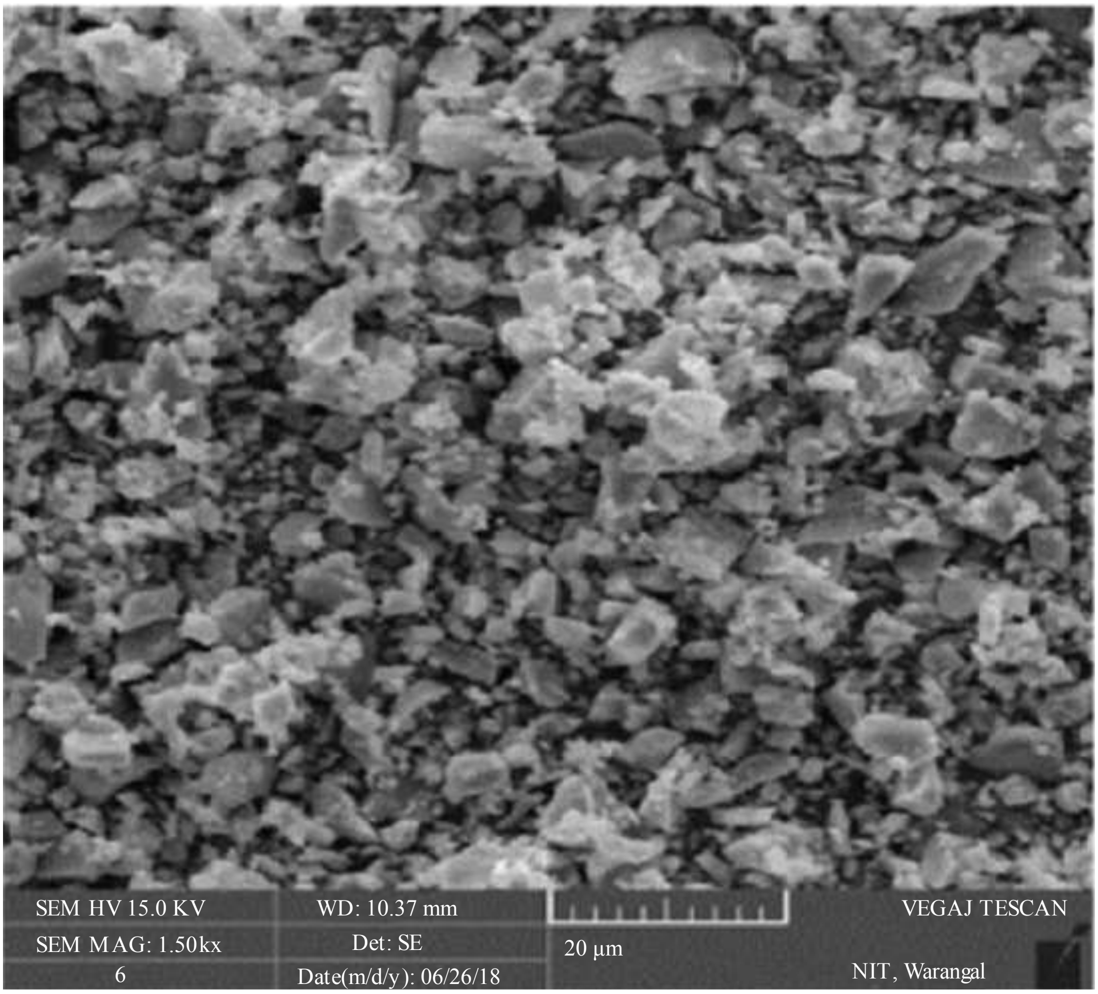


**Figure 2.** Alccofine SEM image.

**Table 2.** Alccofine chemical composition

| Constituent | Calcium oxides | Silicon dioxides | Aluminum oxides | Ferric oxides | Sulfur trioxide | Magnesium oxides | Sodium oxides | Potassium oxides |
|---|---|---|---|---|---|---|---|---|
| Percentage % | 29.46 | 37.53 | 24.57 | 0.92 | 0.18 | 5.23 | 0.032 | 0.61 |

**Fine Aggregate**

M-sand, a crushed fine aggregate made from hard granite stone, is supplied locally. In accordance with IS 383:1970, which outlines the grading standards for fine aggregates used in concrete and mortar, it sieved through 4.75 mm sieve [33]. By applying the physical procedure, the M-sand meets necessary requirements for concrete performance. Table 3 lists the M-sand's physical properties, including its bulk density, specific gravity, particle size distribution, water absorption, and fineness modulus.

**Coarse Aggregate**

The Indian Standard (IS) 383:1970, which specifies requirements for fine and coarse aggregates used in concrete, was utilized to choose the coarse aggregate, which was sourced locally. Coarse aggregate, as defined by IS 383:1970, is made up of particles that are held on a 4.75 mm screen, guaranteeing correct gradation and structural integrity in the concrete mixture. Since crushed stone was used instead of natural gravel, it is likely that the aggregate had angular particles, which can improve the mechanical interlocking between particles and increase the concrete's strength and longevity. In addition to lowering expenses, locally obtained resources guarantee the availability of materials appropriate for the geological and environmental requirements of the research region [32].

 

**Table 3.** Physical properties of M-sand and coarse aggregate

| Physical property | | Sp. gravity | Fineness modulus | Water absorb |
|---|---|---|---|---|
| Test Results | M-Sand | 2.66 | 2.294 | 1% |
| | Coarse Aggregate | 2.67 | 7.67 | 0.5% |

**Table 4.** Mix proportion of nominal concrete, at 16% of alccofine and PWA at 1% to 5% mixes (KN/m$^3$).

| Mix ID | Cement | Alccofine | Fine aggregate | Coarse aggregate | PWA | Water |
|---|---|---|---|---|---|---|
| M0 | 352.80 | 67.20 | 1062.50 | 763.97 | 0 | 163.80 |
| M1 | 352.80 | 67.20 | 1057.93 | 741.14 | 18.28 | 163.80 |
| M2 | 352.80 | 67.20 | 1053.36 | 717.26 | 36.55 | 163.80 |
| M3 | 352.80 | 67.20 | 1048.79 | 693.36 | 54.83 | 163.80 |
| M4 | 352.80 | 67.20 | 1044.23 | 669.48 | 73.10 | 163.80 |
| M5 | 352.80 | 67.20 | 1039.66 | 645.58 | 91.38 | 163.80 |

### Water

Water available on university campus meets the standards specified of mixing and curing concrete as per IS 456:2000, confirming its appropriateness for construction use.

## RESEARCH METHOLODOGY

### Mix Design

The High-Performance Cementitious Concrete (HPCC) mixes were designed in accordance with the guidelines specified in IS 10262:2009. The conventional concrete mix, designated as M0, was prepared using ordinary Portland cement (OPC) and natural coarse aggregate, serving as the reference for performance comparison. To enhance mechanical performance and durability, alccofine a high-reactivity, ultrafine supplementary cementitious material was used to replace 16% of the cement content by weight in all modified mixes and porcelain waste aggregate (PWA), sourced from post-consumer ceramic tile waste, was incorporated as a partial replacement for natural coarse aggregate. The replacement levels of PWA were varied incrementally from 1% to 5% by weight of coarse aggregate. Each modified mix was assigned a unique identifier, designated as M1 through M5, corresponding to the increasing percentage of PWA (1%, 2%, 3%, 4%, and 5%, respectively), while maintaining a constant 16% cement replacement with Alccofine. This systematic substitution approach aimed to evaluate the synergistic effects of dual replacements cement with alccofine and PWA on the fresh and hardened properties of concrete. Table 4 presents the detailed mix proportions for all concrete mixes.

This substitution serves a dual purpose, it supports waste valorization and landfill diversion, and conserves non-renewable natural aggregate resources, aligning with sustainable construction practices. The combination of industrial by-product (alccofine) and recycled ceramic waste (PWA) demonstrates a strategic approach toward the development of eco-efficient concrete with enhanced structural performance and reduced environmental burden.

### Specimen Preparation and Curing

For all HPCC mixtures, cubes dimensions 150×150×150 mm were molded to assess compressive strength at various curing ages. The freshly prepared samples remained undisturbed in the molds for one day to facilitate initial setting. Then specimens were carefully removed from the molds to avoid any damage to their surfaces or edges. Following demolding, the curing process took place at room temperature with complete water submersion of all concrete cubes. The curing durations were set at 7, 14, 28, 56, and 90 days, ensuring an extended observation of strength development over time. Curing plays a crucial role in hydration, enabling the cementitious materials to achieve optimal strength and durability. The 7-day compressive strength results provide an early indication of the concrete's rate of strength gain, while the 14-day strength helps assess the intermediate development. The 28-day compressive strength is considered the standard benchmark for evaluating the overall performance of the concrete mix. Additionally, prolonged curing at 56 and 90 days offers insights into long-term strength development and durability, which is particularly important for high-performance and sustainable concrete applications. This methodical technique to testing and curing aids in comprehending alccofine's and PWA's arguments regarding the strength characteristics of HPCC. providing valuable data for optimizing mix designs for enhanced structural performance (IS 10262:2019 & IS 516:1959).

## RESULTS AND DISCUSSION

### Compressive Strength

An overview of compressive strength values for various concrete mix compositions is shown in Table 5. At 28 and 90 days, the control mix (M0), which was devoid of alccofine and porcelain waste aggregates (PWA), achieved compressed strengths of 43.60 N/mm$^2$ and 53.02 N/mm$^2$, respectively. Nonetheless, addition of PWA and alccofine results in significant improvement in compressive strength of all adjusted mixes. Mix M3, which contains 16% Alccofine and 3% PWA, had the highest compressive strength of all tested formulations. With strength of 44.13 N/mm$^2$ at 28 days and 54.02 N/mm$^2$ at 90 days, this mix significantly outperformed the control mix.

The comparison between mixes M0 and M3 is displayed in Figure 4. The improved strength can have ascribed to the pozzolanic reaction of Alccofine that enhances the microstructure by refining pore size and improving particle packing. Additionally, PWA contributed to further densification of the matrix, leading to improved mechanical performance [33- 35].

Figure 5 (a) & (b) shows that the compression testing of concrete cubes. These findings demonstrate how well alccofine and PWA work as additional cementitious ingredients to increase the strength of HPCC, which makes it a good choice for long-lasting and environmentally friendly building [36].

**Figure 3.** Casting of concrete cubes.

**Table 5.** Compressive strength tests result (N/mm$^2$).

| Mix ID | 7 Days | 14 Days | 28 Days | 56 Days | 90 Days |
|---|---|---|---|---|---|
| M0 | 30.90 | 39.40 | 43.60 | 49.70 | 53.02 |
| M1 | 30.92 | 39.45 | 43.66 | 49.73 | 53.10 |
| M2 | 31.13 | 39.75 | 44.00 | 50.01 | 53.52 |
| M3 | 31.67 | 40.00 | 44.15 | 50.22 | 54.02 |
| M4 | 30.97 | 39.50 | 43.71 | 49.85 | 53.17 |
| M5 | 29.82 | 38.23 | 43.40 | 48.70 | 52.55 |

 

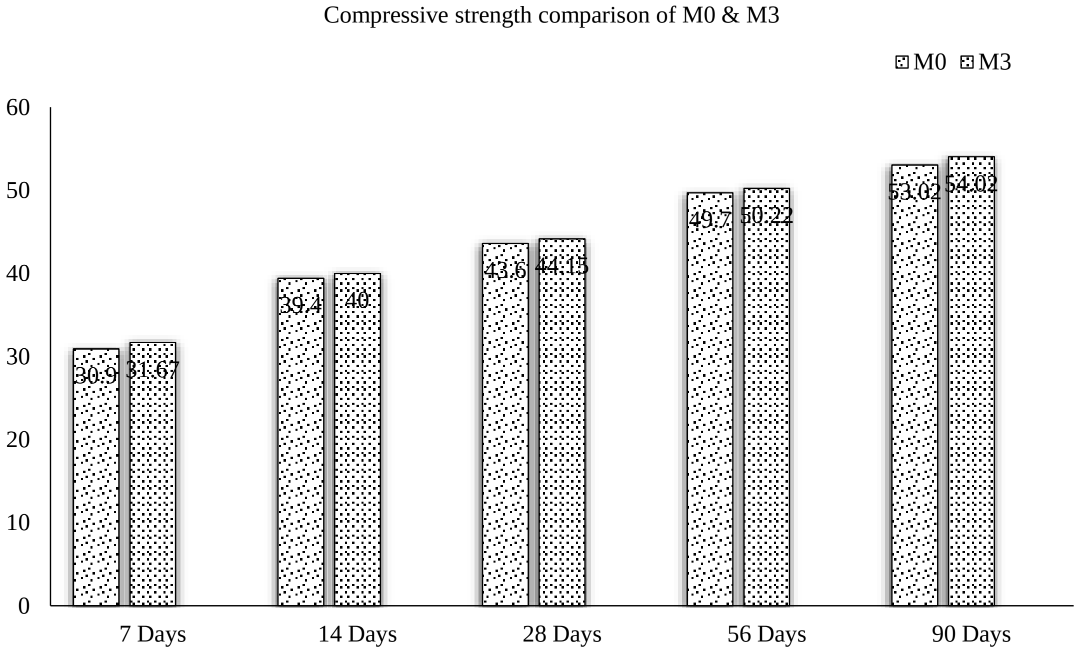


**Figure 4.** The compressive strength comparison of Mix M0 & M3.

**Figure 5.** (a) & (b) compressive strength testing of concrete cubes in compression testing machine.

**Microstructural Analysis**

The SEM (Scanning Electron Microscopy) images revealed a denser microstructure in concrete mixes containing alccofine and PWA (Porcelain Waste Aggregate), particularly in Mix M3. This improved density attributed to two key factors [37]. Mix M3 likely represents an optimized combination of Alccofine and PWA, where the ultra-fine particles of Alccofine and the dense, smooth particles of PWA work together to fill voids and improve the overall packing density. The combination of these substances strengthens the interfacial transition zone (ITZ) which connects the aggregate particles to cement matrix, decrease micro-cracking & refine the pore structure. The denser microstructure shown in the SEM pictures as a result of this synergy is suggestive of enhanced durability, mechanical qualities, and permeability resistance.

 

**Pozzolanic Reaction of Alccofine**

More (C-S-H) gel is produced when alccofine, an additional cementitious ingredient, combines pozzolanically with calcium hydroxide (Ca $(OH)_2$). A denser and more cohesive matrix results from this process, which also helps to fill the pores and refine the pore structure [38]. Alccofine and (Ca $(OH)_2$), a byproduct of cement hydration, react pozzolanically when added to concrete. This general equation describes the reaction.

$SiO_2$ + Ca $(OH)_2$ + $H_2O$ → C-S-H (Calcium Silicate Hydrate)

$Al_2O_3$ + Ca $(OH)_2$ + $H_2O$ → C-A-H (Calcium Aluminate Hydrate)

The additional C-S-H gel contributes to improved compressive strength for better cohesion and improved load-bearing capacity. Reduced permeability leads to higher resistance against chemical attacks, sulfate attack, and alkali-silica reaction (ASR). A crucial step in the hydration process of calcium aluminate cements, the production of C-A-H can affect the mechanical characteristics and setting time. Concrete's long-term performance may be impacted by its stability phases, particularly in harsh settings.

**Particle Packing Effect of PWA**

The packaging density and size distribution of concrete mixture improved when PWA was included. This resulted in a more compact and homogeneous microstructure, reducing porosity, high hardness and durability, Low water demand, compared to natural aggregates, Good angularity, improving mechanical interlocking, Potential pozzolanic reactivity enhancing long-term strength and enhancing the overall integrity of the concrete.

In Figure 6 SEM images revealed a denser microstructure in the mixes containing Alccofine and PWA, particularly in mix M3. The creation of a more uniform and compact ITZ—which is essential for improving mechanical qualities of HPCC was facilitated by pozzolanic reaction of Alccofine and the particle packing effect of PWA. [39].

**X-Ray Diffraction (XRD) Analysis**

X-ray diffraction is one of the important methods for identifying crystalline phases in a material is diffraction analysis. The XRD patterns provide valuable insights into the hydration products and phase composition of concrete mixes containing Alccofine and porcelain waste aggregate. The calcium hydroxide (Ca(OH)2) released from cement hydration and react with silica (SiO2) and alumina (Al2O3) from alccofine during the hydration process. The primary binding phase that gives concrete its strength is C-S-H gel, which is created in excess as a result of this pozzolanic process.

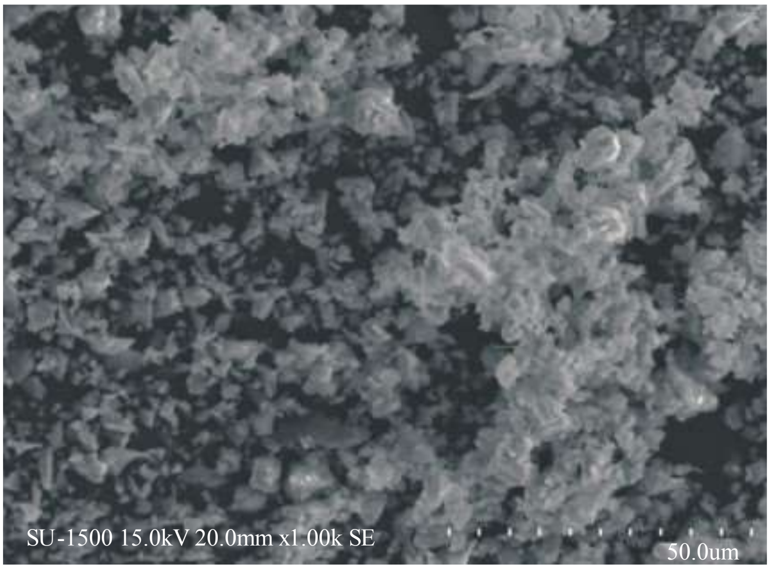


**Figure 6.** M3 mix SEM image at 28 days.

## CONCLUSIONS

The results of this study indicate that incorporating alccofine and porcelain waste aggregate (PWA) significantly enhances the compressive strength of HPCC. This improvement can be attributed to the pozzolanic activity of alccofine, which helps more calcium silicate hydrate (C-S-H) gel to develop, increasing the strength and longevity of the HPCC. Furthermore, PWA's fine particles contribute to the particle packing effect, which results in a concrete matrix that is denser and more compact. When compared to the nominal mix (M0), the different mixes showed varying degrees of enhancement in compressive strength after 28 days. Mix M1 exhibited a 3.25% increase, M2 showed a 4.51% improvement, M3 achieved the highest gain at 7.89%, M4 recorded a 2.16% increase, and M5 demonstrated a 1.38% enhancement. Furthermore, this improvement trend continued over 90 days, demonstrating the long-term strength benefits of incorporating alccofine and PWA. The improvement in compressive strength persisted for ninety days during the cure period. Further validating the effectiveness of Alccofine and PWA in improving durability of HPCC. This sustained strength gain is due to continued pozzolanic reaction of alccofine, It creates a denser and more robust concrete matrix by improving the pore structure and lowering porosity. The optimal mix (M3) demonstrated the highest improvement in compressive strength, proving to be viable option for producing high-performance and environmentally friendly composite concrete. The study's conclusions have important practical and environmental ramifications. By utilizing industrial by-products like alccofine and PWA, Reduced reliance on conventional cement results in fewer cement production-related carbon emissions. Additionally, the effective reuse of porcelain waste aggregates helps in reducing waste accumulation, making this approach enduring sustainable solution for the building sector.

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