Performance Evaluation of Sustainable Concrete Reinforced With Arecanut Fibers And Enhanced By Silica Fume

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Abstract- *In the present time the world wide cement production is about 1.6 billion tons. This huge amount of production leads to consumption of natural resources and it is also harmful for environment. The main components of the gases emitted from cement industries are CO2, N2, O2, SO2, water vapors and micro components i.e. CO and NOx. Large quantity of waste by products are produced from the manufacturing industries such as mineral slag, fly ash, silica fumes etc. The construction industry is increasingly seeking sustainable alternatives to reduce the carbon footprint of concrete and manage agricultural waste. This research investigates the synergistic effect of incorporating Arecanut fibers is a natural fibers obtained from the areca palm tree. It acts as a light weight composite material and silica fume industrial by product found to be an attractive cementations material which is byproduct of smelting process in the silicon and ferrosilicon industry.. The primary objective is to evaluate the mechanical properties of a binary blended concrete mix. In this experimental study, Silica Fume was used as a partial replacement for cement at a constant rate of 10% (by weight), while Arecanut fibers were added in varying volume fractions of 0%, 1%, 2%, 3% and 4%. A control mix of M30 grade concrete was used for comparative analysis. The performance assessment involved testing for fresh properties (slump test), mechanical strength (compressive, flexural, and split tensile strength) of concrete..*

Keywords: Silica fume, Arecanut fibre, workability, compressive strength, split tensile strength test, water absorption test.

I. INTRODUCTION

1.1 Background

The global construction and building infrastructure sectors constitute one of the primary drivers of natural resource consumption and industrial greenhouse gas emissions. Ordinary Portland Cement (OPC), the fundamental binder pinning modern concrete production, is responsible for approximately 7% to 8% of total anthropogenic carbon dioxide (CO2) emissions globally. The manufacturing process of cement is inherently energy-intensive, requiring the calcination of limestone at temperatures exceeding 1450 degrees Celsius, which releases significant quantities of CO2 through both the chemical decomposition of calcium carbonate and the combustion of fossil fuels. As urban expansion accelerates across developing nations, the global demand for concrete is projected to rise exponentially, exacerbating environmental damage and depleting non-renewable raw aggregates. Previously, research findings have shown a lot of interest in SF as it has been found to possess both pozzolanic and micro filler characteristics. It has also been used successfully for the development of high strength concrete using mathematical modeling. However limited test data are available regarding the performance of the commercially available SF and Indian cements in the case of high strength concrete in the country, Hence, carried out this project with Silica fume as a partial replacement of cement.

Silica Fume, also designated as micro-silica, is an exceptional industrial sub-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces during the manufacturing of silicon and ferrosilicon alloys. Physically, silica fume consists of ultra-fine spherical particles with an average diameter of 0.1 to 0.15 micrometers, which is approximately 100 times finer than typical Portland cement particles. Chemically, it comprises more than 85% to 90% amorphous silicon dioxide (SiO2), making it an incredibly reactive mineral pozzolan. When introduced into a fresh concrete matrix, silica fume works through two distinct engineering mechanisms: the physical micro-filler effect and the chemical pozzolanic reaction.

Thus fibres are another to concrete to beat these disadvantages. The addition of fibres within the matrix has several vital effects. Fiber reinforced concrete has been recognized that addition of small, closely spaced and uniformly dispersed fibres to concrete would act as reinforcement to the concrete thereby improves the properties of concrete.

The Fibre concrete (FRC) could be a material primarily consisting of concrete strengthened by random placement of short discontinuous and distinct fine fibers of specific pure mathematics. It's currently well established that the addition of short, discontinuous fibers plays a vital role within the improvement of the mechanical properties of concrete. In the FRC, the fibers facilitate to transfer load to the inner small cracks. Within the recent past, several developments are created within the fiber concrete.

Arecanut husk fiber, a natural and abundant agricultural byproduct, into the concrete mix. Areca nut husk fibers possess unique characteristics that make them suitable for enhancing the mechanical properties of concrete. Areca fiber is an attractive reinforcement for concrete. Thus fibres are another to concrete to beat these disadvantages. The addition of fibres within the matrix has several vital effects. Fiber reinforced concrete has been recognized that addition of small, closely spaced and uniformly dispersed fibres to concrete would act as reinforcement to the concrete thereby improves the properties of concrete.

The experimental approach involves designing and testing various concrete mixtures with different proportions of Silica fume and areca nut husk fiber. Compressive strength tests, split tensile strength and flexural strength test will be conducted to evaluate the performance of these mixtures in comparison to conventional concrete.

The central objective of this MTech research thesis is to comprehensively evaluate the fresh, mechanical, and structural performance parameters of an M30 grade sustainable concrete matrix modified with high-reactivity Silica Fume and reinforced with natural Arecanut Husk Fibers. The specific objectives designed to achieve this target include:

To design and establish a controlled baseline M30 concrete mix proportion conforming strictly to Indian Standard codes IS 10262 and IS 456.

To analyze the fresh-state properties and workability dynamics of concrete mixes when cement is partially replaced with varied percentages of Silica Fume.

To determine the optimum replacement percentage of Silica Fume (ranging from 0% to 40%) that maximizes mechanical compressive strength profiles through accelerated pozzolanic reactions.

To investigate the operational feasibility of incorporating chopped Arecanut Husk Fibers across varied volumetric fractions (1% to 4%) into the optimized Silica Fume concrete matrix.

To evaluate the structural properties of the resulting hybrid composite, specifically tracking cube compressive strength, split tensile strength, and flexural modulus of rupture across 7, 14, and 28-day curing cycles.

To analyze the workability loss mechanisms associated with high fiber loading and establish remedial superplasticizer dosages.

To provide a sustainable structural application roadmap that minimizes carbon footprints and re-utilizes abundant agricultural waste materials.

II. REVIEW OF LITERATURE

This chapter deals with the review of works previously carried out in the area of Silica fume replacement experiments and the role of Areca nut husk fibers in the field of fibre reinforced concrete in the earlier studies are presented. Importance of fibres in toughness and tensile strength point of view and its optimum percentage is also discussed. It is possible to make several classifications among fiber types. Fibers can be divided into two groups, those with elastic moduli lower than the cement matrix, such as cellulose, arecanut, and polypropylene and those with higher elastic moduli such as asbestos, glass, steel, and carbon.

Among all the fibers Areca nut husk fibers have been used in pavements, in shotcrete, and in a variety of other structures. Banana fibers are renewable and obtained from natural resources that present several advantages, including low density, acceptable specific strength properties, good sound abatement capability, low abrasivity, low cost, high biodegradability and existence of vast resources. In addition, at the end of their life cycle these can be incinerated for energy recovery, because they have a good calorific value. New application areas become available as new fiber types and new FRC production techniques are developed.

D Ganesan et al. (2007) conducted a comprehensive evaluation of high-reactivity mineral admixtures, concluding that silica fume exhibits superior pozzolanic efficiency compared to fly ash and blast furnace slag during the first 28 days of curing. They reported that the optimal cement replacement level typically falls between 10% and 20%. Beyond 20%, they noted a dilution effect where the reduction in primary cement content limits the availability of calcium hydroxide, leaving excess silica fume to act merely as an inert filler. This finding underscores the necessity of identifying the precise chemical equilibrium point for specific mix designs.

Patil et al. (2014) investigated the performance of high-strength concrete modified with silica fume and reported that the interfacial transition zone (ITZ) undergoes a structural transformation. In conventional concrete, the ITZ is characterized by a high concentration of large, oriented calcium hydroxide crystals and a high local porosity, making it the weakest region under mechanical stress. The introduction of silica fume replaces these weak crystalline arrays with a dense, homogeneous network of C-S-H gel, resulting in a substantial increase in both compressive and split tensile strength profiles.

Ghutke&Bhandari Examine the Influence of silica fume in concrete. Results indicated that the silica fume is a better replacement of cement. The rate of strength gain in silica fume concrete is high. Workability of concrete decreases as increase with % of silica fume. The optimum value of compressive strength can be achieved in 10% replacement of silica fume. As strength of 15% replacement of cement by silica fume is more than normal concrete. The optimum silica fume replacement percentage is varying from 10 % to 15 % replacement level.

III. MATERIALS AND METHODS

The experimental investigation work is started with various tests on the constituent materials. The constituent materials are given below.

1. Cement
2. Coarse aggregate
3. Water
4. Silica fume
5. Arecanut fibre

1. Cement

Ordinary Portland cement of 43 grades manufactured by Shree Ultratech Cement was used throughout the Experimental investigation. The quality of the cement was confirming to IS 8112:1989 was used in the field.

2. Fine Aggregate

Fractions from 4.75 mm to 150 microns are termed as fine aggregate. Locally available river sand passed through 4.75mm IS sieve is applied as fine aggregate conforming to the requirements of IS 383:1970.

3. Coarse Aggregate

Coarse aggregate shall be of hard broken stone of granite shall be of hard stone, free from dust, dirt and other foreign matters. The stone ballast shall be of 20mm and down and should me retained in 5mm square mesh and well graded such that the voids do not exceed 42 percent. Aggregate most of which is retained on 4.75-mmIS Sieve and containing only so much finer material as is permitted for the various types described in this standard.

4. Silica fume

Silica fume is a byproduct in the reduce of high-purity quartz with coke in electric arc furnaces in the manufacture of silicon and ferrosilicon alloys. Micro silica consist of fine element with a surface area on the order of 20,000 m²/kg when particular by nitrogen adsorption techniques, with particle just about one hundredth the size of the average cement Because of its excessive fineness and high silica content, micro silica is a very efficient pozzolanic material particle. Addition of silica fume also decrease the permeability of concrete to chloride ions, which protect the reinforcing steel of concrete from corrosion, especially in chloride-rich environment such as coastal region. It has been reported that the pozzolanic reaction of silica fume is very important and the no evaporable water content decreases between 90 and 550 days at low water /binder ratios with the addition of silica fume.

5. Arecanut fibre

Arecanut fiber (ANF) is a natural fiber obtained from the areca palm tree. It acts as a light weight composite material

Fig 3.1 Arecanut fiber

IV. MIX DESIGN

The property of workability, therefore, becomes of vital importance. The mix design is done as per IS 10262-2009. Percentage dosage of super plasticizer (high range water reducers) is an additional parameter to be considered for designing an OPC mix. Percentage dosage of super plasticizer was fixed as per the mix design method described in IS 10262-2009. Mix proportion was arrived through various trial mixes. The grade of concrete prepared for the experimental study was M30.

V. RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

This This session provides an outline of the experimental results and endeavors to draw some conclusions. The take a look at result covers the workability, mechanical properties and sturdiness properties of concrete with and while not admixtures. The experimental program was aimed to study the strength of concrete in which Cement was replaced by Silica fume to find the optimum content there after arecanut fibers are added. To study the properties of concrete, mix of M0 is considered. Casting of standard cubes, cylinders and beams for regular concrete and Silica fume with and without addition of Arecanut fibers. The scheme of experimental program as follows. The proportions of the control OPC concrete mixtures were M30. Compressive strength, flexural strength for various mixes then studied the durability with addition of arecanut fibres of varied percentages.

5.2 SLUMP TEST

Slump test was carried out to measure the workability of various mixes. The workability of various mixes was assessed as per the IS 1199:1959 specification. The minimum workability for MIX I may be due to the lesser fine particle size of cement which can result in higher water consumption thereby reducing workability.

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In Phase I, substituting cement with silica fume caused a gradual decrease in slump values from 95 mm (SF0) to 62 mm (SF4). This reduction is driven by the ultra-high specific surface area of the silica fume particles, which increases internal water demand to fully wet the particle surfaces, leaving less free water available to lubricate the mix.

In Phase II, the introduction of arecanut husk fibers led to a more rapid drop in workability, with the slump decreasing to 35 mm at 4% fiber content despite an increased superplasticizer dosage. The randomly oriented fiber filaments form an interlocking internal mesh that physically restricts the mobility of the coarse aggregates, increasing internal friction and resisting flow. To maintain acceptable compaction conditions, superplasticizer dosages had to be increased from 0.8% to 1.8% for high-volume fiber mixes.

5.3.1 COMPRESSIVE STRENGTH

The main function of the concrete in structure is mainly to resist the compressive forces. When a plain concrete member is subjected to compression, the failure of the member takes place, in its vertical plane along the diagonal. The vertical cracks occur due to lateral tensile strain. A flow in the concrete, which is in the form of micro crack along the vertical axis of the member will take place on the application of axial compression load and propagate further due to the lateral tensile strain.

Cubes are prepared of size 150 mm x 150 mm x 150 mm are checked for compressive strength. The specimens tested for 7, 14 and 28 days. The specimen were tested for compressive strength parallel to the plane of the board by applying increasing compressive load until failure occur. The arrangement of load is applied to the specimen by placing the specimen length vertical between the surfaces of the testing machine. Prior to that, measurement for the thickness and width was carried out in order to get the values of cross section area for the test specimens.

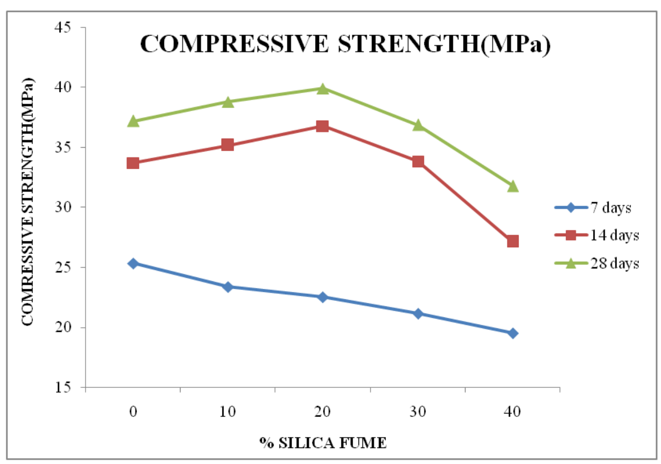

Fig 5.2 Plot shows the Variation in Compressive Strength for % Silica fume

5.4 EVALUATION OF SPLIT TENSILE STRENGTH PERFORMANCE

The split tensile strength of the M30 grade concrete mix with partial replacement of cement by silica fume and arecanut fibers showed higher strength against splitting after 7 and 28 days of curing. The split tensile strength of the mix containing a 20% partial replacement of silica fume showed higher strength compared to the other mixes. Table 6.3 shows the summarized split tensile strength results for the different curing periods of the M30 grade concrete.

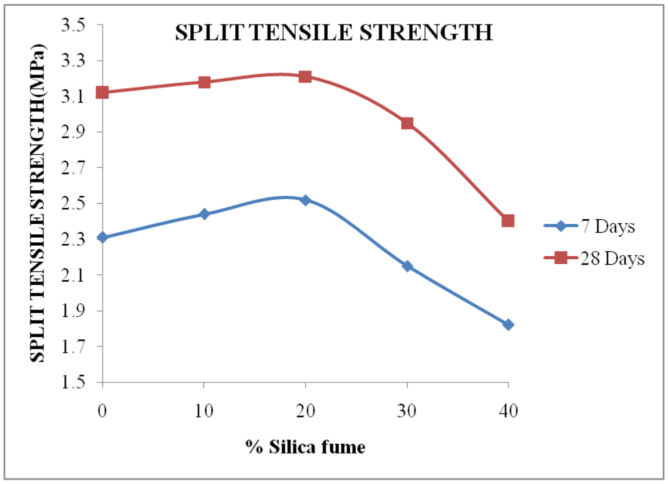

Fig 5. Plot shows the Variation in Split tensile Strength for % Silica fume

5.6 FLEXURAL STRENGTH

The size of specimens 100 mm x 100 mm x 500 mm was used and the specimens were cured in water. Concrete specimen beams are used to determine flexural strength of concrete and were tested as per as per IS 516 (1959).

Flexural strength of concrete keeping 20% Silica fume as constant and with different percentages of arecanut fibre for curing period of 7-days, 14-days and 28-days.

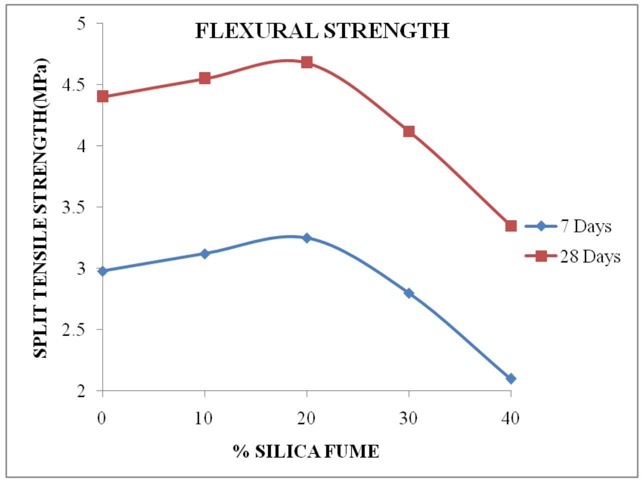

Fig 5.5: Plot shows the Variation in flexural Strength for % Silica fume

5.7 VARIATION OF STRENGTH FOR ADDITION OF ARECANUT FIBRES TO OPTIMUM PERCENTAGE OF SILICA FUME

strength of concrete keeping 20% Silica fume as constant and with different percentages of arecanut fibres for curing period of 7-days and 28-days respectively and Table shows the summarized strength Results for different curing periods– M30 grade.

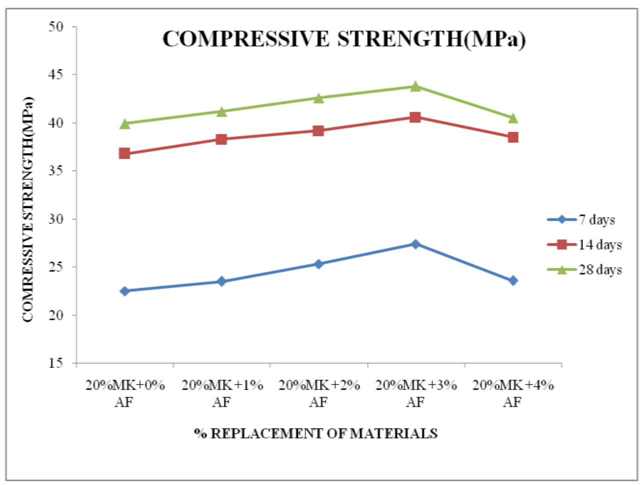

Fig 5.6: Shows the Variation in Compressive Strength for % Arecanut Fibers to optimum percentage of Silica fume

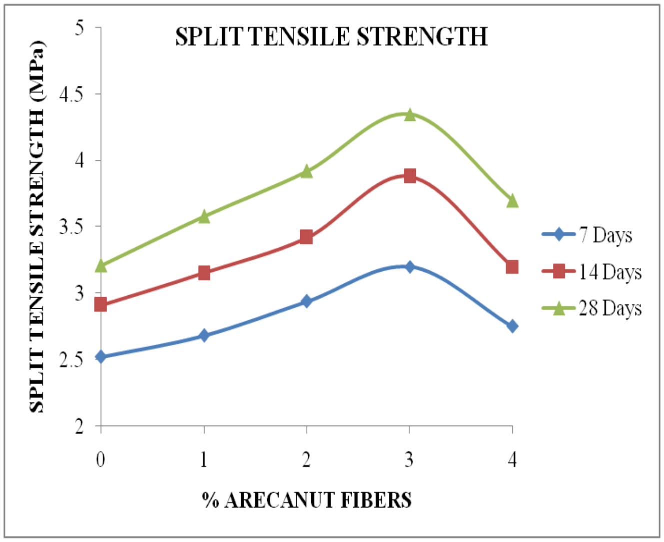

Fig 5.7: Plot shows the Variation in Split Tensile strength for different percentages of Arecanut fibers

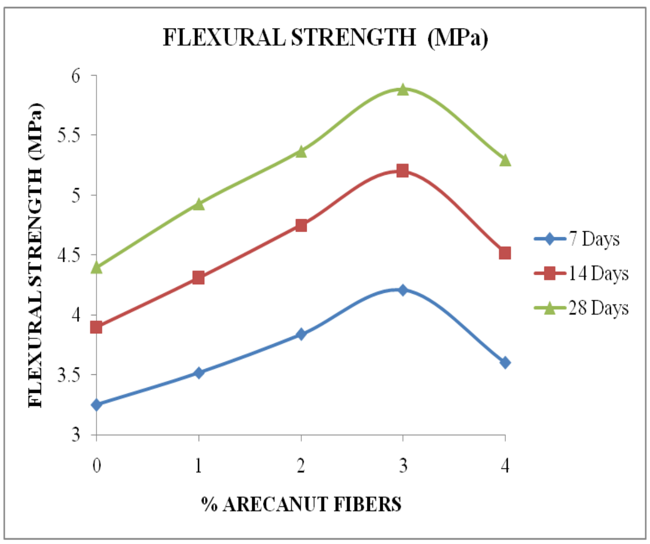

Fig 5.8: plot shows the variation in flexural strength for different percentages of arecanut fibers

From the results, it is evident that as the fiber content increases, the tensile performance of the concrete improves, resulting in higher strength values compared to those of plain concrete.

The figures illustrating the test results for both splitting tensile strength and flexural strength after water curing demonstrate that the percentage increase in strength is directly proportional to the increase in fiber content. Furthermore, the experimental data indicates that the compressive and flexural strengths also increase with the addition of fiber content

VI. CONCLUSIONS

Based on the extensive laboratory-scale experimental investigation conducted to evaluate the performance parameters of an M30 grade sustainable concrete matrix modified with high-reactivity Silica Fume and reinforced with natural chopped Arecanut Husk Fibers, the following core engineering conclusions are drawn:

Fresh State –Workability

- The fresh-state workability (slump flow) of the concrete decreases progressively across both experimental phases.
- Partially substituting cement with silica fume lowers the slump from 95 mm (SF0) to 62 mm (SF4). The addition of natural chopped arecanut husk fibers causes a more rapid, mechanical drop in workability, pulling the slump down to a minimum of 35 mm at a 4% volume fraction (SF2-AF4). This is driven by the interlocking behavior of the filament mesh, which physically restricts aggregate mobility and intensifies internal matrix friction.

Supplementary Cementitious Binder Performance

- The optimal partial cement substitution level was determined to be **20% Silica Fume (SF2)**. At 28 days of curing, the SF2 mix achieved a peak compressive strength of **39.93 MPa** (a 7.31% increase over the control mix's 37.21 MPa) , a split tensile strength of **3.21 MPa** , and a modulus of rupture of **4.68 MPa**.
- Increasing substitution levels beyond this boundary (30% and 40% in SF3 and SF4) leads to a substantial decrease in mechanical capacities, with the 28-day compressive strength plummeting to 31.80 MPa for SF4. This drop occurs due to a dilution effect where lower clinker content limits available $Ca(OH)2$, leaving excess silica fume to act as an unreacted, highly porous filler.

Fiber-Reinforced Concrete Matrix

- Using the optimized 20% silica fume binder as a fixed matrix, introducing chopped arecanut fibers (50 mm length, aspect ratio 57) provides exceptional upgrades to the composite's mechanical strength, fracture toughness, and cracking resistance.
- The maximum synergy across all mechanical parameters was structurally isolated at a **3% volumetric fiber loading threshold (SF2-AF3)**.

- The optimal hybrid composite (**20% SF + 3% AF**) yielded the following structural results across its water-curing cycles:
    - **Compressive Strength:** Progresses from 27.40 MPa at 7 days to **43.82 MPa** at 28 days, marking a **17.76% enhancement** over the unreinforced OPC control concrete.
    - **Split Tensile Strength:** Increases from 3.20 MPa at 7 days to **4.35 MPa** at 28 days, providing an optimal defense against longitudinal splitting stresses.
    - **Flexural Strength (Modulus of Rupture):** Rises from 4.21 MPa at 7 days to **5.89 MPa** at 28 days, establishing a massive **33.86% structural leap** over the reference baseline concrete.
- Increasing the fiber content to 4% (SF2-AF4) results in a structural drop-off across all profiles (e.g., 28-day compressive strength drops to 40.55 MPa, and flexural strength drops to 5.30 MPa). This reduction is due to localized fiber balling, non-homogeneous dispersion, and the entrapment of large internal microstructural air voids during table vibration.

Environmental and Sustainability Impacts

- This project demonstrates that integrating industrial by-products (Silica Fume) with local agricultural residues (Arecanut Husk Wastes) provides a viable pathway for high-performance, eco-friendly civil infrastructure elements.
- Utilizing these materials reduces the clinker factor of standard concrete mixtures, which lowers the massive carbon footprint and greenhouse gas intensity associated with traditional Ordinary Portland Cement production.
- Furthermore, redirecting agricultural husks into concrete production offers a constructive alternative to the open-field burning or decaying of commercial palm residues, encouraging a circular economy in regional sub-tropical construction sectors.

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