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PARTIAL REPLACEMENT OF CEMENT WITH ALCCOFINE AND MARBLE DUST FOR THE DEVELOPMENT OF SUSTAINABLE CONCRETE

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Abstract

Concrete is the most extensively employed building material globally, with cement as its principal binding agent. However, cement manufacturing is highly energy-intensive and contributes to approximately 8% of global CO_2 emissions, posing serious environmental and sustainability challenges. Moreover, the extraction of raw materials required for cement further leads to natural resource depletion. To address these concerns, this study investigates the partial replacement of cement with Alccofine—a high-performance ultrafine slag material—and Marble Dust, a waste by-product from the marble industry. Various concrete mixes were prepared with 10% and 20% Alccofine, combined with 5% and 10% Marble Dust, and their compressive strength was evaluated at 7 and 28 days. The results indicate that mixes incorporating Alccofine and Marble Dust show marked improvement in strength compared to the control mix (21.5 MPa at 7 days and 30.2 MPa at 28 days). Notably, the mix containing 20% Alccofine and 5% Marble Dust achieved the highest strength, with 24.1 MPa at 7 days and 34.2 MPa at 28 days, demonstrating a significant enhancement in performance. This study confirms that sustainable concrete can be developed using industrial by-products without compromising strength, promoting both environmental conservation and improved material efficiency.

Keywords: Sustainable Concrete, Alccofine, Marble Dust, Cement Replacement, Compressive Strength.

1. Introduction

The construction sector is a significant consumer of natural resources and a primary contributor to global greenhouse gas emissions, largely attributable to the widespread utilization of Portland cement in concrete manufacturing. The production of cement contributes around 7-8% to worldwide carbon dioxide produced and represents a substantial existential risk to the environment [1, 2]. Priority over the past few years has been to create substitute construction materials that minimize damaging environmental effects without compromising structural performance [3]. A promising approach is concerned with the partial replacement of cement by "Supplementary Cementitious Materials (SCMs)" that include

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many industrial waste or by-products [4-6]. This has the benefit of both reducing cement's carbon footprint and eliminating that waste.

Application of supplementary cementitious materials also be effective in fulfilling the increasing demand for high performance concrete. Experience indicates that high strength concrete is typically designated as such when it meets the criteria of elevated cement quantity and a low ratio of water to cement [7, 8]. Alccofine and marble dust can be classified under potential SCMs, which can be utilized efficiently in concrete for enhancing its mechanical properties and durability while maintaining [9, 10]. Alccofine is microfine material consisting primarily of calcium silicate-based materials. Moreover, alccofine is a by-product of ferroalloy production. Alccofine is classified as a microfine compound because of the ultra-fine particle size and high pozzolanic reactivity and high specific surface area [11]. When used as an additive in concrete, it will act as filler space and react with calcium hydroxide to form “Calcium Silicate Hydrate (C-S-H)” gel. The C-S-H occupy the pore space and lead to a denser microstructure and enhanced compressive strength, durability, and resistance to adverse environment conditions [12]. In addition, Alccofine fineness enhance the workability and packing density in concrete mix. Additionally, Alccofine also impart the characteristics of early strength gain and low permeability, which is desirable for high-performance and durability purposes in concrete [13].

In contrast, “Marble Dust (MD)” is a by-product of the process of cutting, shaping, and polishing using marble. MD is mostly made up of calcium carbonate and is generated in great quantities in marble-producing countries. MD disposal poses environmental issues such as air and water contamination due to its very fine and alkaline nature [14, 15]. Employing marble dust in concrete, either in place of cement or fine aggregate, provides a sustainable means of disposing of this waste product. Marble stone dust served as filler and filled in to add weight to the concrete matrix. While marble dust lacks pozzolanic activity, the fineness and amount of lime can enhance the surface finish, decrease porosity, and enhance some mechanical properties of the concrete when applied in proper proportions [16, 17]. And the utilization of marble dust in concrete reduces the consumption for virgin natural materials as well as waste materials.

Use of Alccofine and marble dust synergistically in concrete compositions is a novel combination to ensure a balance between pozzolanic and filler effects for concrete performance and sustainability. While Alccofine offers a pozzolanic reaction that plays an important part in the strength and durability of concrete, marble dust improves the microstructure and reduces the amount of cement used [18]. Their combined impact may result in production of sustainable concrete that requires less raw materials, costs less to produce, and ends up performing optimally for a longer period of time. The characteristics of such industrial waste products are also consistent with circular economy paradigms of waste utilization and preservation of resources [19]. Partial substitution of Alccofine for cement and marble dust must be studied to determine their individual and combined influences on fresh as well as hardened properties of concrete at various levels of replacement, concrete

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performance variables like as functionality, breaking strength, flexible strength, retention of water, and permanence need to be systematically evaluated [20].

The present study explores this potential, aiming to augment the expanding corpus of knowledge regarding sustainable concrete technologies and to provide a viable pathway for environmentally conscious infrastructure development. The current research encourages sustainability due to environmental issues and resource depletion with regard to supplying traditional cement to buildings. Since the study has concluded, Alccofine and marble dust were utilized as cement partial replacement to supply sustainable substitutes but ensuring proper or better strength characteristics. The research makes an experimental contribution in the sense that Alccofine and marble dust are shown to be industrial wastes, and they have the ability to produce performance attributes for concrete while promoting environmentally friendly construction materials and products. The research contains a literature review of existing research on the use of alternative cementitious materials like Alccofine and marble dust, including real descriptions of materials, such as: mix designs, testing methods of concrete and presentation of compressive strength results are presented in the results section, suitable conclusions followed by future research directions are also provided. The study begins with a literature survey reviewing past work on alternative cementitious materials. Research then outlines the materials used, mix designs, and testing methods employed to assess concrete performance. The results section presents the compressive strength outcomes, following with conclusion encapsulates the results and proposes avenues for future investigation.

2. Literature review

New development in sustainable concrete has recently brought into focus the deliberate incorporation of mineral admixtures like Alccofine and marble dust to offset cement's requirement while defining mechanical abilities. **Durai et al. (2025) [21]** carried out a comprehensive study where GGBFS (30 %), Alccofine (15 %), and Metakaolin (10 %) were blended, yielding gross improvements in compressive, tensile, and flexural strength, up to 90 days. **Gayathri et al. (2025) [22]** also reported highly useful application of 10 % Alccofine with recycled aggregate concrete (RAC) with an outstanding 39.74 MPa compressive strength, far exceeding target strengths. In light of **Durga et al. (2025) [23]** also discussed that high performance concrete using 20 % Alccofine produced mean flexural strength of 8.11 N/mm² compared to normal mixes. In general, these results solidly imply the effect Alccofine had on the mechanical behavior of a series of grades of concrete, with and without added binders as fly ash or silica fume, also confirmed by **Karthik et al. (2023) [24],** who obtained enhanced performance and mechanical behavior with 15 % Alccofine under alkali curing.

When considering the partial replacement with the waste marble dust, the findings have been inconsistent but, overall, encouraging. For instance, **Sathe et al. (2024) [25]** illustrated that the substitution of 5% of the cement with marble powder enhanced the 3-day strength, by up to 25%. However, further substitutions exhibited inconsistent trends in strength. **Ali et al.**

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(2024) [26] discovered that substituting 10% cement with waste marble dust enhanced compressive strength but also discovered that substituting sand would limit strength loss more effectively. Similarly, **Majeed et al. (2021) [27]** also discovered a reduction in concrete density due to MDP possessing a lower specific gravity than cement, which presents the potential to utilize the characteristics of lightweight construction. In addition, **Rid et al. (2022) [28]** and **Mhamal et al. (2023) [29]** both found that the replacement of fly ash or granite dust with marble dust led to improved mechanical performance of the mortar and eco-strength efficiency and that the best performance was at 10–20% replacement. Thus, this research indicate that marble dust indeed maintains sustainable properties; however, it is clear that various properties influence its value: mixes, percentage, and paired materials.

Thus, the combination of both Alccofine and MD together could offer additional synergetic properties that can be beneficial in the creation of sustainable high-performance concrete. Although Alccofine has been found to improve densification and the development of early strength because of its high reactivity and small particle size, such as has been achieved in UHPC uses by **Gautham Kishore Reddy & Ramadoss (2020) [30],** marble dust mainly exhibits filler effect, and partial binder dilution. The filling properties of Alccofine with marble dust, particularly with planned substitution ratios, can bring about an optimal balance of performance, when the qualities of concrete are compared, in terms of its strengths, durability, and sustainability. While **Ahmadi et al. (2023) [31]** and **Kumar et al. (2022) [32]** suggested that long-term durability tests like impact resistance, and synergy with fiber reinforcement, must be carried out to lead to long-term sustainability. Thus, further work needs to be directed towards the utilization of industrial waste products as ternary mixes, in order to facilitate provision of overall performance criteria.

Even though numerous investigations on Alccofine and marble dust as partial cement substitutes have been conducted, there exists a substantial disparity in research regarding the combined effects of both materials on the mechanical, durability and environmental characteristics of concrete. Previous investigations mostly examined Alccofine or marble dust alone or with different levels of replacement with no consideration of the synergy between both materials together. Additionally, there is little investigation into the best mix design in seeking an enhanced strength of concrete with durability and sustainability and whether or not curing conditions and harsh environments would change this. The qualitative comparison of ternary or binary blended systems for Alccofine and marble dust remains missing to generate definitive and reproducible guidelines in enhancing construction sustainability with the use of these materials as a combination. Which justifies this study to investigate the synergetic effects of Alccofine and marble dust when used together on concrete properties and to develop a sustainable high-performance mix that minimizes environmental impact without compromising structural performance.

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3. Materials and Methods

The method employed in the present study was to evaluate the effect of partial cement replacement with Alccofine and MD on the compressive strength of concrete. A systematic experimental procedure was adopted, including the selection of materials; mixing preparation; castings; curing; and strength testing at specific time intervals as shown in figure 1.

3.1 Material selection

a) Conventional Materials used

Cement

Cement is the most important binding material in concrete. Cement react chemically with water and harden into a strong and durable bind, and one that holds the aggregates together. “Ordinary Portland Cement (OPC)” is the most widely used cement and is mainly made of calcium silicates, calcium aluminate and calcium ferrite. The fineness, chemical composition, and setting time of the OPC all play a decisive role in figuring out the workability of the concrete, the strength of the concrete, and the durability of the concrete. Cement also plays a significant contributing role to the heat of hydration and shrinkage expression during the curing process, and controlling its content in mix design therefore becomes crucial for both structural and environmental performance for the concrete.

Coarse aggregate

Coarse aggregate typically varies from 4.75 mm to 20 mm or larger and denotes bigger sizes that are utilized in concrete. In concrete coarse aggregates are practically always crushed stone or gravel and contribute the strength structure and volume of concrete. Coarse aggregates determine the compressive strength, stiffness, and durability of the concrete. The individual characteristics of the coarse aggregates, including shape and texture, strength, cleanliness, and stability, together influence hardening performance and stability. Coarse aggregate grading and selection issues in concrete mix design to allow for good particle interlocking, low void volume, and most effective strength development.

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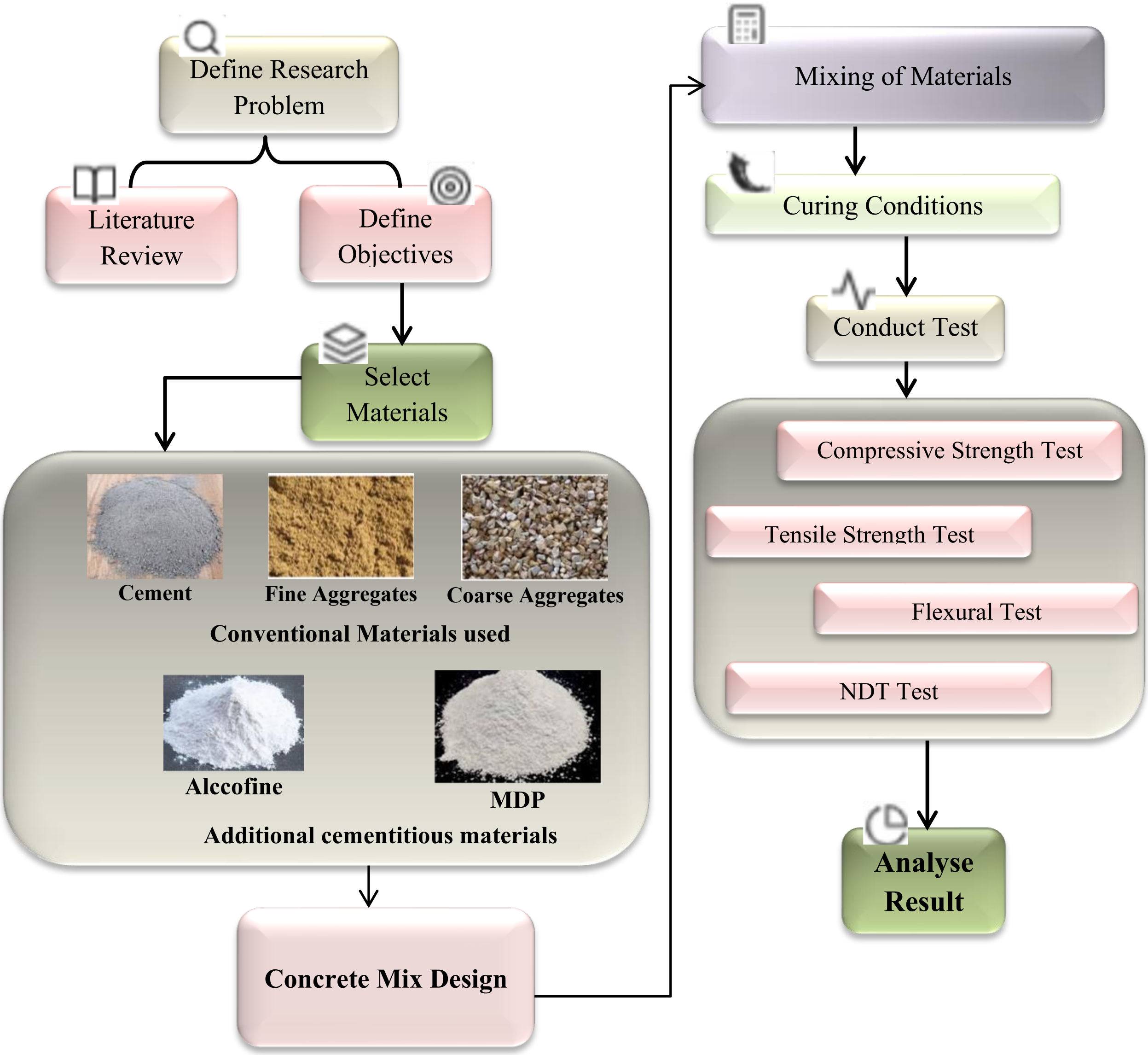

Figure 1: Proposed Framework

Fine aggregate

It is either natural sand or crushed stone with a particle size less than 4.75mm. Fine aggregates occupy the spaces in coarse aggregates, increase the workability of a mix, and yield a more compact concrete matrix. Quality of fine aggregate in terms of gradation, fineness modulus, and cleanliness (absence of clay and silt) is proportional to fresh concrete's consistency, finish, and cohesiveness. Constant proportioning and quality check of the fine aggregate assist in developing strong and crack-free concrete structures.

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Table 1: Property of the conventional materials

Material	Key Properties	Specific Gravity	Role in Concrete
Cement	Fineness, setting time, heat of hydration, chemical reactivity	3.15	Acts as the binder; initiates strength and hardening process
Coarse Aggregate	Size, shape, texture, strength, specific gravity	2.6–2.9	Provides structural skeleton; enhances compressive strength
Fine Aggregate	Gradation, fineness modulus, cleanliness, moisture content	2.6–2.7	Improves workability; contributes to concrete density

b) Alternative cementitious materials

Alccofine

Alccofine is an ultrafine high-performance mineral admixture that is manufactured from slag-based material having mainly calcium silicate and aluminosilicates. It is finer than cement with a median particle diameter (d50) of < 5 microns that provides enhanced pozzoloanic and filler effects. Alccofine behaves similarly to silica fume and plays a major role in concrete strength gain and durability. Alccofine makes a perfect addition due to its ultrafine particle, high rate of reaction, high reactivity, and high surface area of nearly 12000 cm^2/g, which has excellent potential for strength gain, particularly at an early age. It enhances characteristics of concrete/sustainable concrete technology like workability, lowering permeability, enhancing compressive, flexural, and tensile strength. Alccofine has also been successfully employed in self-compacting and high-performance concrete. Alccofine formulation also helped reduce micro-cracking and enhanced packing density in the cementitious matrix. In all, Alccofine is a very effective material in sustainable concrete technology.

Marble dust powder

Marble dust powder (MDP) is a powdered waste product from the polishing and cutting of marble stones with predominantly calcium carbonate ($CaCO_3$). MDP is of a specific gravity of ~2.6 and is finer powder than fine aggregates with 75 microns or finer particle sizes. MDP is widely utilized as a filler material and as a substitute for cement or fine aggregates (in concrete). Addition of MDP to the concrete mixture enhances the compactness of the mixture, hence enhancing the initial strength of the concrete as a result of the micro-filler effect. Technically, MDP reduces the heat of hydration. MDP is a very good substitute for cement and/or fine aggregates (in concrete) based on quantity used, the optimum 5-10% as cement replacement, and enhances eco-efficiency by minimizing processing and waste

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marble disposal. MDP is also useful in enhancing the environmental performance of concrete through recycling of materials and virgin clinker content reduction.

Table 2: Physical parameter of additional materials

Parameter	Alccofine	Marble Dust Powder (MDP)
Appearance	Light grey ultrafine powder	White to off-white fine powder
Specific Gravity	~2.9–3.1	~2.6
Fineness (Blaine)	~12,000 cm²/g	~3,000–5,000 cm²/g
Average Particle Size (d50)	<5 microns	<75 microns
Bulk Density	~600–700 kg/m³	~800–900 kg/m³
Main Component	Calcium Silicate, Aluminosilicates	Calcium Carbonate ($CaCO_3$)
Color	Light grey	White/off-white
Reactivity	High (pozzolanic and filler)	Low to moderate (mostly filler)

3.2 Concrete Mix Design

The mix was specially designed for M30 grade concrete. This is a standard mix employed in structural applications aimed at achieving a CS of 30 MPa at 28 days. The mix contains OPC partially replaced in order to make it more sustainable and minimize environmental footprints [33]. The replacement comprised 15% cement replacement: the first replacement material validated 10% of OPC by Alccofine, an ultra-fine pozzolanic material of high reactivity and the second validated 5% of OPC by MD, a waste product of marble manufacturing utilized as a micro-filler only. The substitutions were intended to reduce carbon emissions, improve durability and durability over time, while preserving similar CS of the concrete mixture.

A W/C ratio of 0.40 was chosen to attain the required strength and minimize porosity. There was batching of a superplasticizer at 1% addition (by weight of the entire cementitious content) for enhancing workability because of the fine particles involved (Alccofine and dust of marble) in every batch, optimizing the flow ability level and maintaining minimal water content. The aggregates were batched conventionally (on modified M30 mix design) with 1.5 parts sand to cementious material and 3 parts coarse aggregate to PCB that ensure grain size distribution and accurate gradation for gain of strength without fear of reactivity. Fine and coarse aggregates were batched on conventional M30 ratio of mix 1:1.5:3 with preventative

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additive quantities of replacement from sand & cementious material adjustment. The last batch proportions of concrete per m³ are as given in the following table 3:

Table 3: M30 Concrete Mix Proportions with 10% Alccofine and 5% Marble Dust (per m³)

Material	Quantity (kg/m³)
Cement (OPC)	297.5
Alccofine (10%)	35.0
Marble Dust (5%)	17.5
Water	119.0
Fine Aggregate (Sand)	446.25
Coarse Aggregate	892.5
Superplasticizer (1%)	3.0

This mix is designed such that binder's function best, minimizing OPC and enhancing overall sustainability, using SCMs from waste sources. Alccofine's pozzolanic reaction will contribute towards early strength and durability, with marble dust acting as a filling agent, or packing agent, for additional efficiency in compacting. Workability will be sustained by incorporating a superplasticiser. Standard trial batching and quality control testing (slump, compressive strength) assist in determining field performance, and then adjustments can be made based on local materials and characteristics.

Mixing M30 Grade Sustainable Concrete

Input:

- Grade of Concrete: M30
- Cement replacement: 10% Alccofine, 5% Marble Dust
- Water-Cement Ratio (W/C): 0.40
- Superplasticizer Dosage: 1% of binder
- Mix Ratio: 1 : 1.5 : 3 (Binder : Fine Aggregate : Coarse Aggregate)

Steps:

1. Start
2. Define Target Strength ← 30 MPa
3. Set W/C Ratio ← 0.40
4. Set Superplasticizer Dosage ← 1% of total binder weight
5. Set Binder Composition:

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- Cement ← 85% of binder
- Alccofine ← 10% of binder
- Marble Dust ← 5% of binder

6. Measure Materials:
   - Calculate weights of cement, Alccofine, and marble dust
   - Calculate weight of fine aggregate (sand) using ratio 1.5 × binder
   - Calculate weight of coarse aggregate using ratio 3 × binder
   - Calculate water = W/C × binder
   - Calculate superplasticizer = 1% × binder
7. Begin Mixing:
   - Mix dry binders (cement + Alccofine + marble dust) for 2 minutes
   - Add sand and mix for 1 minute
   - Add coarse aggregate and mix for 1–2 minutes
8. Add Water + Superplasticizer Solution:
   - Gradually add while mixing continuously
   - Mix wet contents for 3–4 minutes until uniform
9. Check Workability:
   - Perform slump test
   - If required, adjust water or superplasticizer slightly (maintain W/C)
10. Cast Concrete:
    - Place in molds
    - Compact using vibrator or tamping rod
11. Curing:
    - After 24 hours, demold samples
    - Cure for 28 days in water or under moist conditions
12. End

Output:

Uniform, sustainable M30 grade concrete mix with improved durability and workability

3.3 Curing of the Concrete

After the freshly mixed concrete is poured into designated moulds or structural elements, the process of curing becomes vital to ensure optimal hydration and strength development. Curing supplies moisture for hydration and conditions to facilitate strength and hydration growth for a long period (typically at least 28 days). Curing is required so that cementitious materials fully hydrate. Curing encourages a controlled environment for hydration, which restrict moisture loss and form a more compact, stronger microstructure eventually.

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In this sustainable mix of concrete with marble dust and Alccofine used at 10% and 5% as partial cement replacements, curing is a necessary step to realize the performance advantage of such supplementary materials. Once cast, the specimens are set at controlled temperatures; in this period, i.e., curing and hardening, Alccofine participates in secondary hydration reactions with CH from cement hydration. They form C-S-H, the main strength contributor in concrete. Hence, the composite concrete contains more C–S–H formed by hydration subsequent to the casting which ultimately results in a more compact mix of concrete, and better early as well as long-term compressive strength.

3.4 Testing

Concrete testing is necessary to assess its performance in fresh as well as hardened state. Fresh concrete is normally tested for workability using tests like the slump cone test to determine correct mixing and sufficient ease of placing and operation. Fresh concrete is most often cast and cured for a specific period before testing for performance in hardened forms. Hardened concrete samples, being compressive strength-tested, are typically evaluated after 28 and 7 days of curing using a compression testing machine. Other testing of concrete includes tensile strength through split-cylinder testing and flexural strength testing through beam bending tests. Such testing is useful in identifying if the mix of concrete suffices for structure/function and durability requirements to meet the structural performance as intended.

4. Results and Analysis

This results section outlines the findings from compressive strength tests conducted on concrete samples of different proportions of Alccofine and MDP. The outcomes show how the introduced material influences the mechanical characteristics of concrete.

Compressive strength testing determines the strength of the concrete under axial loading (compression) and is one of the significant parameters of structural integrity of concrete for usage like buildings and bridges. Standard concrete cubes (150 mm × 150 mm × 150 mm) were cast and cured for 28 days and then loaded in a “Compression Testing Machine (CTM)”, which went on until structural failure for this research. The CS was calculated from dividing the final sustained load by the cross-sectional area. Alccofine, which enhances hydration with ultra-fine particles, forms a denser microstructure that also enhances strength. Marble Dust Powder enhances the density of the concrete through filling micro-voids within and hardening the matrix. The findings of the work show the influence of admixture materials on the CS of concrete and for structural use.

Table 4: Concrete samples containing marble dust and alccofine had their compressive strengths compared to the control mix.

Sample	Alccofine (%)	Marble Dust (%)	Compressive strength 7 days (Mpa)	Compressive strength at 28 days (Mpa)

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Control	0	0	21.5	30.2
Mix 1	10	0	22.4	31.6
Mix 2	20	0	23.0	32.5
Mix 3	0	5	21.9	30.8
Mix 4	10	5	23.2	33.0
Mix 5	20	5	24.1	34.2
Mix 6	10	10	22.8	32.3
Mix 7	20	10	23.4	33.5

The table 4 indicates the measured CS values of the concrete specimens with different proportions of Alccofine and MDP as a partial replacement of cement, against the control mix with 0% replacement. The compressive strengths were tested at 7 days and 28 days to compare the early performance and the normal curing performance. The mix of control was 21.5 MPa and 30.2 MPa at 7 days and 28 days, respectively. In general, compressive strength was found to be higher with a higher addition of Alccofine and Mix 5 (20% Alccofine and 5% MD) produced the maximum strengths of 24.1 MPa and 34.2 MPa at 7 days and 28 days, correspondingly. The blend of 10% Alccofine and 5% Marble Dust (Mix 4) also showed significant improvement over the control values. Based on these findings, the Alccofine and MD appear to have a combined, synergistic effect, which enhances the hydration of the concrete and densities the matrix, with higher CS in general. According to the findings of the investigation, the compressive strength of concrete increases when its cement has been partially replaced with a mixture of alccofine and marble dust and are strongest after 28 days curing. The highest strength was obtained using 20% alccofine and 5% marble dust.

Table 5: Compressive strength with different percentages of Alccofine and MDP replacement

Label for X-Axis	7-Day Strength	28-Day Strength
ALC 10% + MDP 0%	22.4	31.6
ALC 20% + MDP 0%	23.0	32.5
ALC 0% + MDP 5%	21.9	30.8
ALC 10% + MDP 5%	23.2	33.0
ALC 20% + MDP 5%	24.1	34.2
ALC 10% + MDP 10%	22.8	32.3
ALC 20% + MDP 10%	23.4	33.5

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The table 5 and figure 2 presents the CS of concrete mixes which utilized different proportions of Alccofine and MDP as partial cement replacements. The result of the data reveals that the higher percentage of Alccofine, particularly when blended with 5–10% of MDP, produces significantly enhanced 7 day and 28-day compressive strength. The graph shown represents these results, where each combination indicates greater strength at both curing ages, namely the ALC 20% + MDP 5% mixture had the greatest strength at both curing ages. But slightly beyond both optimal percentages, there was a different drop in strength, showing over-replacements can have the contrary effect. Overall, the evidence proves that blended cementitious materials not only enhance early and long-term concrete strength but promotes sustainable construction.

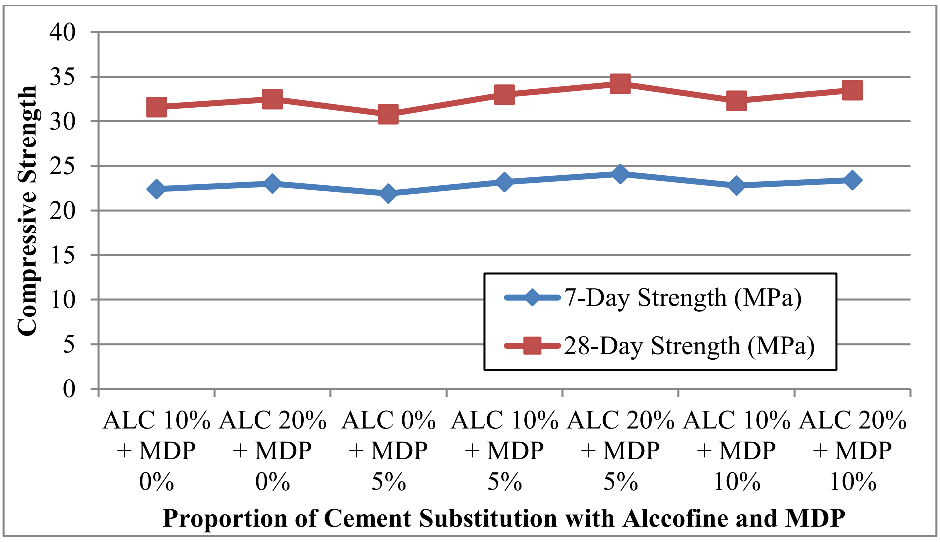

Figure 2: Analysis of split tensile strength over every combination

The slump test was employed for testing the workability. There was a minor decrease in slump because of the addition of marble dust and alccofine, which indicates that the increase in mixtures stiffness on replacement. Nevertheless, all the combinations were within an acceptable range for most, if not all, construction uses. Alccofine and Marble Dust Concrete had greater resistance to water penetration and acid attack, as indicated by the durability tests of acid resistance and water absorption where varying rates were used of Alccofine.

5. Conclusion

The present study demonstrates that the partial replacement of cement with Alccofine and MDP significantly enhances the CS of concrete, contributing toward the development of more sustainable and durable construction materials. The experimental study validates the effectiveness of partially replacing cement with Alccofine and marble dust to produce sustainable and high-performance concrete. The results indicate a consistent improvement in CS across all modified mixes compared to the control mix, which recorded 21.5 MPa at 7 days and 30.2 MPa at 28 days. Mix 1 (10% Alccofine) achieved 22.4 and 31.6 MPa, while Mix 2 (20% Alccofine) reached 23.0 and 32.5 MPa, confirming the strength-enhancing

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properties of Alccofine due to its ultrafine particle size and improved hydration. Similarly, the inclusion of marble dust at 5% in Mix 3 resulted in a moderate increase in compressive strength (21.9 and 30.8), highlighting its ability to fill microvoids and improve the concrete matrix. Notably, the combination of 20% Alccofine and 5% marble dust in Mix 5 recorded the highest strengths—24.1 MPa at 7 days and 34.2 MPa at 28 days—demonstrating a synergistic effect that improves mechanical performance and microstructural density. Compared to the control mix, all modified mixes demonstrated superior strength values, confirming the potential of these industrial by-products in reducing cement consumption and environmental impact. Future scope includes exploring long-term durability aspects such as resistance to sulfate attack and carbonation, as well as studying the behavior of these mixes in real structural applications and varying climatic conditions.

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