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EVALUATING THE EFFECTS OF COMBINED FLY ASH AND MARBLE COARSE AGGREGATES ON THE PROPERTIES AND DURABILITY OF CONCRETE

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Abstract

This study highlights the potential of marble waste and fly ash as sustainable alternatives to natural aggregates in the concrete industry. Rapid developments in infrastructure, urbanization, and industrial growth are increasing global demand for concrete, putting pressure on natural resources and threatening ecological balance. To address these challenges, incorporating recycled materials, such as marble aggregates and fly ash, into concrete presents a promising solution that reduces the use of virgin resources and CO_2 emissions while maintaining the essential properties of concrete. This study explores using environmentally friendly concrete by replacing natural coarse aggregates with marble coarse aggregates from local industries and substituting some cement with class F-fly ash from power plants. The objective is to optimize concrete properties without sacrificing strength. The examination methods, including Ultrasonic Pulse Velocity and the rebound hammer, were chosen to comprehensively and non-destructively assess the strength and durability of the concrete. They enable the confirmation of mechanical properties while effectively comparing results with destructive tests for a more precise analysis of the impact of recycled materials. Various concrete mixtures with different levels of marble waste and fly ash are compared to conventional concrete made entirely of natural aggregates. Fly ash replaces 10% of the cement, while natural coarse aggregates are replaced with marble aggregates in proportions ranging from 10% to 90%, increasing by 20%. Mixtures with marble aggregates show an increased slump, while mixtures with 10% fly ash have a slightly lower slump. Replacing 10% of the cement with fly ash and 70% of natural aggregates with marble aggregates improves compressive strength by approximately 9.94%, 13.5%, 23.83%, and 24.04% on days 7, 14, 28, and 56. Concrete containing marble aggregates and fly ash demonstrates normal ultrasonic pulse velocity and a satisfactory correlation between destructive and non-destructive tests.

Keywords: Compressive Strength, Fly ash, Marble coarse replacement, Schmidt Hammer, Ultrasonic velocity, Workability.

1. Introduction

Concrete is a widely used composite material and a key element in developing global infrastructure. It ranks second, after water, in terms of usage, with a global production of around 5.3 billion cubic meters annually [1]. According to Mehta, and Monteiro [2], this production is expected to reach 18 billion tons by 2050.

Concrete consists of three main components: water, aggregates, and cement. Cement, the primary ingredient in concrete, acts as a binding agent when combined with water and aggregates in its powdered form.

Cost-effective, adaptable, and durable, concrete is also mouldable into various shapes and finishes, making it a versatile material. It has high compressive strength (the ability to withstand forces that compress or crush the material), but low tensile strength (the ability to resist forces that attempt to stretch or tear the material), limited ductility (the ability of concrete to deform without breaking under stress), and low crack resistance (the ability to resist the formation of cracks under stress or temperature variations). As a result, durability has become an increasing concern in the construction sector.

Concrete production is reported to account for 8% of global carbon dioxide emissions [3], with Portland cement being a major contributor [4], which exacerbates environmental pollution [5]. Thus, while concrete is essential for infrastructure development, its ecological impacts highlight the need to explore more sustainable alternatives and rethink production methods to reduce its ecological footprint.

The extraction of all raw materials for concrete, sourced directly or indirectly from the Earth's crust, has exacerbated the global depletion of these resources. As a result, significant environmental and economic concerns have arisen due to the widespread use of concrete. This necessitates a total or partial replacement of cement and aggregates with an environmentally friendly substance. In this context, we anticipate two objectives: the first aims to reduce the CO_2 emissions generated by cement manufacturing. In contrast, the second seeks to mitigate environmental effects by using residual industrial materials as fine/coarse aggregates or as alternatives to cement.

Over the last century, researchers have suggested some industrial and agricultural waste products. Among them are silica fume, which improves concrete's compressive strength and durability, and ground granulated blast furnace slag, which can reduce the carbon footprint while increasing concrete’s resistance to heat and moisture. Rice husk ash, in addition to being a low-cost material, offers pozzolanic properties that enhance concrete performance, while marble waste, often considered an industrial by-product, can partially replace aggregates, thus reducing dependence on natural resources.

On the other hand, textile sludge ash and sewage sludge ash provide significant economic and ecological benefits by contributing to waste management while reducing the need for raw materials. These materials, whose production has significantly increased in response to rapid economic growth and increased global energy consumption, contribute to industrial and agricultural waste accumulation. Their use as substitutes in concrete production is crucial for reducing the overall environmental impact by diverting these materials from landfills and decreasing the demand for natural resources.

Marble waste is produced during marble cutting, while fly ash is a byproduct of coal combustion in thermal power plants, classified into Class F and Class C. Class F fly ash has over 70% silica, aluminium, and iron oxide, with low calcium content, enhancing concrete's pozzolanic properties and reducing water demand. Class C fly ash contains 50% to 70% of these oxides. Utilizing both materials can improve concrete performance and promote sustainability.

Within research by Binici et al. [6], 100% of the natural coarse aggregates in concrete were replaced by waste marble, with the replacement measured by weight, while maintaining a constant water-to-cement ratio of 0.4 by weight.

In various studies, marble aggregates were used as replacements for traditional coarse aggregates in concrete. Hebhoub et al. [7] found that increasing the substitution rate of marble aggregates led to a decrease in workability, but compressive and tensile strengths improved by 16% to 25% at a 75% replacement rate. Gencel et al. [8] observed a 40% reduction in the unit weight of concrete mixes when substituting marble waste in varying proportions (0%, 10%, 20%, 40%). André [9] reported a 50% increase in compressive strength with up to 50% marble aggregate substitution, with strength decreasing beyond this point.

In another study, André et al. [10] found no significant difference in durability between concrete with conventional aggregates and concrete using up to 100% marble waste, although workability decreased at 50% substitution. Hakan and Sedat [11] noted that marble aggregates fully replacing traditional aggregates achieved the desired strength at all curing ages and showed improved surface hardness and ultrasonic pulse velocity. Martin et al. [12] observed slight reductions in density (0.28% to 4.21%) and tensile and compressive strength (1% to 10.4% and 5.2% to 6.2%, respectively) at marble replacement levels between 20% and 100%. Workability increased by 4.16% to 9.34% across the mixes.

The waste marble was utilized in place of traditional coarse aggregates in research by Ahmed et al. [13]. They claimed that improvements had been made to the mechanical and physical qualities of concrete. Because of the marble aggregate's low water absorption and smooth, level surface, the concrete mixtures became 50% more workable. Furthermore, it was stated that, in contrast to the control mixture, the flexural and compressive strengths of the concrete including marble aggregates grew by 11.44% and 29.62%, respectively.

Throughout the investigation conducted by Kore and Vyas [14], the effects of using leftover marble as a partial replacement for conventional coarse aggregates on the workability, compressive strength, permeability, and abrasion resistance of concrete mixtures were investigated. The natural coarse aggregates, representing 75% of the total weight, were replaced by marble coarse aggregates. Test findings showed compressive strength like that of traditional concrete. Furthermore, there was a decrease of roughly 30% and 15%, respectively, in durability attributes like permeability and chloride ion penetration. In contrast to traditional concrete, the absorption of water was reduced by 17%, and there was a 2% increase in abrasion resistance.

In their respective studies, Sahu et al. [15] and Sowjanya et al. [16] investigated the effects of replacing natural aggregates with marble-based substitutes. Sahu's research showed that using 10% waste marble in place of natural coarse aggregates resulted in concrete with strength comparable to that of conventional concrete, measured by compressive strength values at 28 days according to standard testing.

Meanwhile, Sowjanya used black marble coarse aggregates to replace natural aggregates at varying proportions: 0%, 20%, 40%, 60%, 80%, and 100%.

The study found that replacing natural aggregates with black marble coarse aggregates improved conventional concrete workability. Substituting 40% of natural coarse aggregates led to a peak in the concrete's compressive strength.

Numerous studies have investigated the optimal amount of fly ash as a cement substitute, focusing on workability, compressive strength, density, and modulus of elasticity in comparison to traditional concrete. Ghazali et al. [17] found that replacing up to 20% of cement with fly ash improved workability, while a 10% replacement yielded the highest compressive and flexural strength among the mixtures tested. Providing specific metrics for measuring workability would enhance these findings.

Fly ash was used as a partial cement substitute at 20% and 40%, achieving compressive strength comparable to reference samples. The study of Seeni et al. [18] examined 10% increments of fly ash up to 40% and included larger aggregates (12.5 mm and 20 mm). Results showed that 20% fly ash improved the mechanical properties of permeable concrete. Recommendations include ensuring consistent terminology and capitalization, presenting percentages uniformly, and clarifying the importance of curing times. However, adding a higher proportion of fly ash resulted in a decrease in compressive strength after 28 days of curing. In research conducted by Damodhara et al. [19], fly ash is used to replace cement at substitution levels of 0%, 5%, 10%, 15%, 20%, and 25%. According to the published findings, by substituting 10% of fly ash for cement, the compressive strength of the specimen is increased by 32.63% at 28 days, 29.25% at 56 days, and 16.93% at 90 days.

This research is distinguished by its innovative methodology, integrating fly ash and marble waste in concrete formulations. This study distinguishes itself from prior research by investigating the synergistic effects of these materials as partial substitutes for cement and natural coarse aggregates, while assessing their influence on the mechanical properties of concrete, including compressive strength, tensile strength, and workability.

This research introduces an experimental formulation that evaluates the optimization of a blend comprising 10% fly ash and up to 70% marble as a substitute for natural aggregates, to enhance concrete durability while preserving its mechanical properties. This stringent experimental framework facilitates practical applications in sustainable concrete.

Another contribution is the implementation of the “SonReb” method, which integrates two non-destructive testing techniques to assess the compressive strength of recycled concrete. This methodology addresses the shortcomings of conventional techniques, providing an innovative means to evaluate the efficacy of sustainable concrete.

2. Research Relevance

The primary objectives of this study are to minimize environmental degradation and reduce reliance on natural resources. Our research aims to examine the properties of concrete when 10% fly ash is used to replace cement, and marble coarse aggregates are substituted for 10% to 90% of natural coarse aggregates, increasing in increments of 20%. The water-to-cement ratio is maintained at 0.5.

Concrete samples produced with these modifications are evaluated for workability, Schmidt rebound hammer index, split tensile strength, flexural strength, ultrasonic pulse velocity, and compressive strength. By closely examining the consequences of these changes on the composition and performance of concrete, we aim to assess this alternative approach's feasibility and environmental benefits, emphasizing the potential broader impacts on sustainability.

3. Experimental study

3.1. Characterization of materials

Portland cement CPJ 45, with a minimum clinker content of 65%, was chosen as the binder due to its favourable mechanical properties and adherence to Moroccan specifications NM10.1.004. The concrete mix incorporates water supplied by the Autonomous Intercommunal Water and Electricity Distributing Agency of Oujda (RADEEO), which meets the physical and chemical standards outlined in NM 10.1.353. Ensuring high water quality is crucial for achieving optimal mechanical properties and long-term strength in the concrete.

Natural sand sourced from the Oujda region was selected for its minimal impurities, exhibiting a specific gravity of 2.68, water absorption of 2.5%, and a fineness modulus of 2.85. Its smooth, spherical, and cube-like shape contributes to good workability. To manage the water content, the sand was dried at room temperature for a full day, with a maximum particle size of 4.75 mm, following the NF EN 12620 standard for sand testing. Two varieties of crushed coarse stone aggregates, designated G1 and G2, were employed, with nominal sizes of 10 mm and 20 mm, respectively. Their specific gravities were measured at 2.70 and 2.72, and water absorptions were recorded at 1.48% and 1.50%, as specified by the NF P-18-560 standard.

As an auxiliary material in the process of shaping and cutting, marble companies provided marble dust in the form of Coarse Aggregate. Marble waste was crushed into the crusher to obtain a size ranging from 5 to 20 mm. The Marble Coarse Aggregate (MCA) has a specific gravity of 2.73 and water absorption of 0.50%.

F-class fly ash sourced from the Jerada thermal power plant in Morocco was used in the mix. This material, collected via electrostatic dust collection from flue gas streams of pulverized coal boilers, is characterized by its low calcium content (1.18%), a Blaine fineness of 3360 m^2/kg, and a specific gravity of 2.2, as specified by NM 10.1.004. Its fine particles and low calcium composition contribute to improved concrete strength and durability.

Table 1 presents the initial and final setting times, consistency, and specific gravity of the sand and coarse gravel, as well as the Blaine fineness of the cement and fly ash, fineness modulus, and water absorption results. Table 2 displays the chemical constituents of the natural aggregates. Figure 1 shows the particle size analysis of the different materials utilized.

The materials were subjected to physical and chemical tests to assess their suitability for the concrete mix. Physical tests included analyses of density, water absorption, and particle size distribution of the aggregates and fly ash, following NF EN 12620 and NM 10.1.004 standards. Consistency and setting time tests were also conducted to measure the behaviour of the fresh concrete. Chemically, the materials were analysed to determine their chemical composition, including the calcium content of the fly ash and the elements present in the natural and marble aggregates, to ensure they meet the required specifications for mechanical performance and durability of the concrete. These tests validated the quality of the materials and their ability to meet the project's requirements.

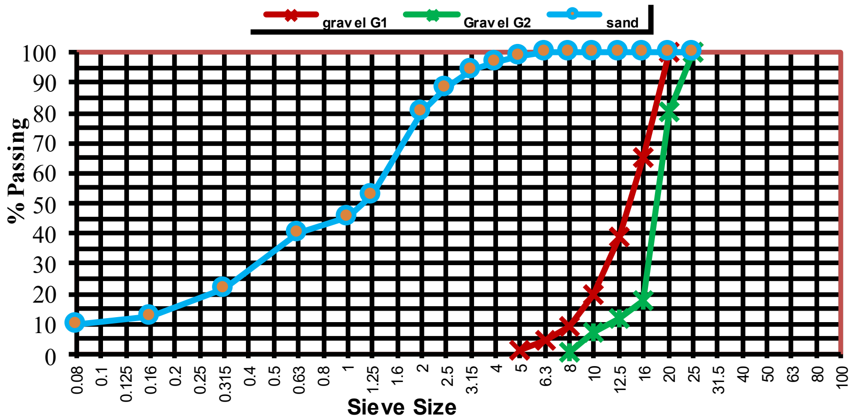

Fig. 1. Distribution of sand, gravel G1, and gravel G2 particle sizes.

Table 1. Physical characteristics of cement, fly ash, sand, coarse aggregate G1, G2, and marble coarse aggregate (MCA).

Property	Cement	Fly Ash	Sand	G1	G2	MCA
Specific Gravity	3.15	2.20	2.68	2.70	2.72	2.73
Water absorption %		3.01	2.50	1.48	1.50	0.5
Consistency (%)	29					
Fineness modulus		0.96	2.85	6.62	6.82	7.68
Initial setting time (min)	180					
Final setting time (min)	210					
Fineness Blaine (cm^2/gm)	3100	3360				

Table 2. The chemical constitution of cement, fly ash and sand.

Constituent (%)	Cement (%) by mass	Fly Ash (%) by mass	Sand (%) by mass
CaO	60.06	1.18	5.58
SiO_2	20.90	55.2	77.40
Fe_2O_3	3.90	11.2	2.66
AL_2O_3	5.85	28.3	8.18
MgO	1.85	0.68	0.77
K_2O	2.14	1.45	0.25
TiO_2	0.32	1.5	0.005
SO_3	2.35	0.44	0.018
LOI	21.84	1.06	

This study aims to assess how the partial substitution of fly ash and marble aggregates influences the mechanical properties and overall performance of concrete.

The water-to-cement ratio of 0.5 is crucial for achieving optimal workability, strength, and durability in concrete, ensuring proper hydration and bonding between aggregates and cement paste.

We chose 10% fly ash, and 10% to 90% marble aggregates based on previous research showing their positive effects on concrete mechanical properties. The 10% fly ash increases durability and strength, while the range of marble aggregates allows for the study of how different substitution rates affect concrete performance and optimizes recycled material use. The choice of proportions in this research was guided by previous studies and international specifications related to recycled materials in concrete.

The proportions were determined based on the results of prior research on the impact of incorporating fly ash and marble aggregates on the mechanical properties of concrete. Standards such as those from the American Concrete Institute (ACI) and Moroccan specifications were also considered to ensure that the proposed mixes meet performance and durability requirements. These factors helped optimize the proportions to achieve a balance between the strength, durability, and environmental sustainability of the concrete.

The mixture ratios of fly ash, marble aggregate, and cement are listed in Table 3. The symbol CF indicates fly ash used in place of cement, and CAM indicates coarse marble aggregates instead of natural aggregates. For example, CF10-CAM30 refers to the mixture in which fly ash is employed instead of 10% of the cement and 30% of the natural aggregates are replaced with alternative aggregates.

Table 3. Mixture proportions with w/c=0.5.

Mix identification	fly ash (%)	CAM (%)	Water Kg/m^3	Cement Kg/m^3	FA Kg/m^3	G1 Kg/m^3	G2 Kg/m^3	fly ash Kg/m^3	CAM Kg/m^3
CF0-CAM0	0	0	175	350	763	327	833	0	0
CF0-CAM10	0	10	175	350	763	294	750	0	116
CF0-CAM30	0	30	175	350	763	229	583	0	348
CF0-CAM50	0	50	175	350	763	164	416	0	580
CF0-CAM70	0	70	175	350	763	98	250	0	812
CF0-CAM90	0	90	175	350	763	33	83	0	1044
CF10-CAM0	10	0	175	315	763	327	833	35	0
CF10-CAM10	10	10	175	315	763	294	750	35	116
CF10-CAM30	10	30	175	315	763	229	583	35	348
CF10-CAM50	10	50	175	315	763	164	416	35	580
CF10-CAM70	10	70	175	315	763	98	250	35	812
CF10-CAM90	10	90	175	315	763	33	83	35	1044

3.2. Test parameters

The experimental program was designed to assess concrete mixes in a controlled environment, utilizing the facilities at the laboratory of the Oujda Faculty of Science, which provides state-of-the-art equipment and resources for concrete research. Additionally, the LABNORVIDA testing laboratory in Oujda is recognized for its specialized testing capabilities and commitment to stringent quality standards. We carefully formulated the concrete mixtures using a 125-liter capacity pan mixer, a crucial size for the project that facilitates the efficient blending of larger batches, ensuring uniformity and consistency in the resulting concrete.

The mixing process commenced with the introduction of coarse aggregates to the mixer, followed by the addition of fine aggregates. We initially added a limited quantity of the total calculated water to facilitate the dispersion of the dry ingredients and prevent premature hydration, which could compromise the workability and uniformity of the final concrete mixture. We subsequently integrated the cement, fly ash, and marble aggregates before adding the remaining water. A uniform mixture was crucial for ensuring the equitable distribution of all components, directly affecting the concrete's strength, durability, and overall efficacy.

3.2.1. Workability

The workability of each concrete mix was assessed through a standardized slump cone test in accordance with NF EN 12350-2 to investigate the effects of partially replacing 10% of cement with fly ash and substituting varying percentages of Marble Aggregates (10%, 30%, 50%, 70%, and 90%) for Natural Coarse Aggregates. The slump cone, with a height of 300 mm, a bottom diameter of 200 mm, and a top diameter of 100 mm, was utilized for all tests. Slump values were documented for each mixture, offering insights into the flow and consolidation characteristics of the concrete, which are essential indicators of the workability and overall performance of freshly mixed concrete.

3.2.2. Compressive strength

A concrete structure's compressive strength is a crucial indicator of its load-bearing capability, which is necessary to guarantee durability and safety. To assess this property, 150 mm x 150 mm x 150 mm concrete cubes were cast and cured in a controlled environment with 100% relative humidity and a constant temperature of 27 ± 2 °C. These conditions are essential for getting accurate strength readings. In compliance with NF EN 12390-3 standards, we conducted compressive strength tests at curing ages of 7, 14, 28, and 56 days; we generally recognize the 28-day mark as the benchmark for evaluating concrete strength.

We carefully mixed the components to ensure even distribution, then meticulously poured them into the moulds to reduce the formation of air bubbles, preserving the density and integrity of the samples. We vibrated the concrete to ensure adequate compaction, remove voids, and produce a uniformly smooth surface essential for precise strength testing. Compressive universal testing machine as shown in Fig. 2.

Fig. 2. Compressive universal testing machine.

3.2.3. Ultrasonic pulse velocity

Ultrasonic pulse velocity testing is a non-destructive method that can be used to check the quality of concrete in place. This is important for checking the strength of concrete structures without damaging them. This testing follows the NF EN 12504-4 standard procedure, ensuring reliable and accurate results. We used a voltage of 500 V and a frequency of 54 kHz for the test. These are important settings for getting the most out of the ultrasonic testing process.

Figure 3(a) shows the testing tool, which is made up of a pulse-sending and receiving processor unit that checks the time between sending and receiving the ultrasonic pulses. The device attaches two probes that exchange sound energy. Timing the sound wave's journey between these two probes, where the sending probe sends sound energy into the concrete and the receiving probe picks up the energy, allows us to determine the pulse speed. Figure 3(b) illustrates how to determine the pulse flow rate by examining both sides of the concrete. We put concrete cube samples through ultrasonic pulse velocity tests after 28 days of curing to assess their quality.

Fig. 3(a). Sonic inspection device.

Fig. 3(b). Direct transparency measurements.

3.2.4. Schmidt rebound hammer

Evaluating the compressive strength of concrete is essential to ensure safety and structural integrity in construction. The Schmidt Rebound Hammer is an instrument that measures this strength using a process based on the rebound of a spring-driven hammer. When pressed against the surface of the concrete, the hammer is released and strikes the surface, causing it to rebound. The distance the hammer rebounds is directly related to the hardness of the concrete surface: harder concrete allows for a higher rebound.

This non-destructive testing method provides an estimate of the concrete strength according to the NF EN 12504-2 standard. The readings from the rebound hammer are correlated with the compressive strength of the concrete using conversion charts provided by the manufacturer. These charts are based on extensive testing that establishes correlations between rebound values and actual concrete strength. In practice, a user interprets the hammer readings by consulting the conversion charts, allowing for a quick and effective determination of concrete strength on-site. Schmidt rebound hammer as shown in Fig. 4.

Fig. 4. Schmidt rebound hammer.

4. Results and conversational analysis

4.1. Marble powder's impact on the concrete's workability

The workability of concrete mixtures is essential for ensuring ease of placement and proper compaction, thereby influencing the final quality of the structures. The F-class fly ash, rich in silica and alumina, is a byproduct of coal combustion, commonly used as a cement supplement in concrete. In this study, the workability of the mixtures was evaluated by incorporating 10% F-class fly ash as a replacement for cement. Additionally, natural coarse aggregates were replaced with marble aggregates at rates ranging from 10% to 90%. The use of fly ash improves the workability and durability of the concrete while reducing cement consumption, thereby promoting more sustainable construction practices.

The replacement rates and slump values of the mixtures are detailed in Table 4, indicating that the slump values of fresh concrete vary from 57 to 72 mm, which aligns with the target slump range S2 (plastic concrete) as per the NF EN 12350-2 standard.

We observed that mixtures containing marble coarse aggregates exhibit an increase in slump compared to conventional concrete. Furthermore, Fig. 5 demonstrates that concrete with over 50% marble aggregates and 10% fly ash as a cement substitute, as well as concrete with only marble coarse aggregates rather than natural aggregates, has higher initial slumps than regular concrete. This improvement is attributed to the smooth surfaces of marble coarse aggregates and their higher shape index compared to natural aggregates. The difference between the round fly ash particles and the angular cement particles also makes it easier for the mixture to flow and move around because the particles do not rub against each other as much.

Table 4. Slump values.

Mix designation	Slump (mm)
CF0-CAM0	57
CF0-CAM10	58
CF0-CAM30	58
CF0-CAM50	62
CF0-CAM70	65
CF0-CAM90	66
CF10-CAM0	62
CF10-CAM10	63
CF10-CAM30	64
CF10-CAM50	68
CF10-CAM70	71
CF10-CAM90	72

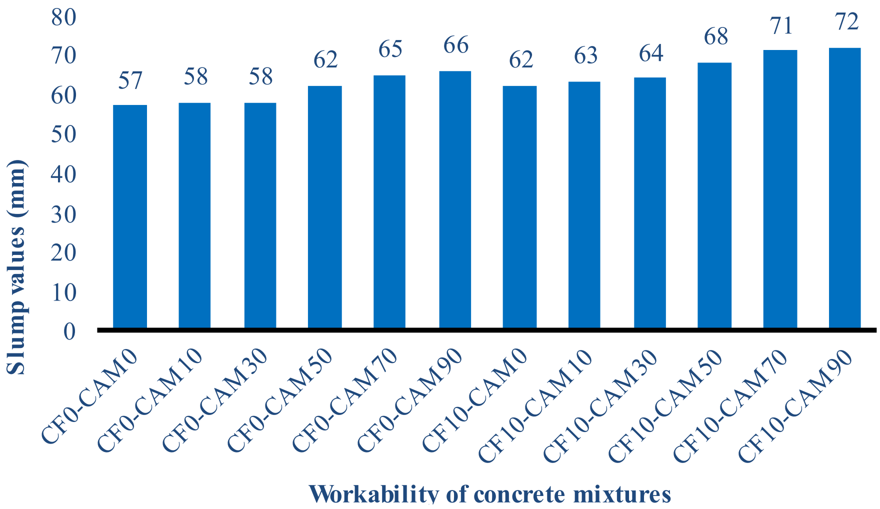

Fig. 5. Workability of concrete mixtures.

4.2. Impact of coarse marble aggregates and fly ash on compressive strength

To determine how well concrete performs, how much weight it can support, and how long buildings will last, compression strength tests are necessary.

After being cured with water, samples of concrete were used to test their compressive strength. For this process, the samples had to be submerged in water during the whole curing time to keep the right amount of moisture. They were left to dry for 24 hours before being analysed at 7, 14, 28, and 56 days old. The time for curing was increased to 56 days to account for the fly ash's slow pozzolanic reaction.

Three samples were used to get the average, which is what is usually done for all tests to make sure the results are accurate. A universal testing machine (UTM) was used to get the compressive strength results. The compressive strength values for each sample are shown in Table 5 and Fig. 6. The 56-day compressive strength for concrete with up to 10% fly ash as a partial cement replacement and up to 90% coarse marble aggregates is between 15.72 MPa and 37.25 MPa.

This research revealed that replacing 10% of the cement with fly ash leads to a faster decrease in compressive strength compared to the control concrete. At 7, 14, 28, and 56 days, the samples that used marble aggregates instead of 70% of the natural coarse aggregates showed improvements of 22.15%, 24.76%, 22.58% and 22.61%.

Furthermore, the compressive strength improves by almost 9.94%, 13.5%, 23.83%, and 24.04% at days 7, 14, 28, and 56, respectively, when 10% fly ash is substituted for cement and 70% of the natural coarse aggregates are replaced with marble.

The results with these values can be attributed to the selection of fly ash, marble aggregates, and other materials at specific substitution rates, as well as the specific combination of these materials. Furthermore, a thorough examination of the properties of the material and the curing environment is crucial to the outcome of these findings.

The pozzolanic action, which slows secondary hydration during the early stages, a drop in compressive strength for concretes, including fly ash, at early ages. While the pozzolanic reaction adds more CSH gel to the concrete, enhancing its strength at days 28 and 56, the presence of fine fly ash particles fills the pores and alters the characteristics of the transition zone surrounding the aggregates.

Unlike natural aggregates, which have a rough texture, the smoothness of marble aggregates limits the adhesion between the marble particles and the cement paste, weakening the mechanical bond. This reduced adhesion leads to a less efficient interface between the aggregates and the cement matrix, negatively affecting the concrete's mechanical strength. As the applied force is transferred less effectively between the cement paste and the aggregates, concrete containing marble aggregates at unstudied substitution levels shows a decrease in both compressive and tensile strength. In the case of our study, the combination of fly ash and marble aggregates did not affect the compressive strength compared to the control concrete.

Given that the CF10-CAM70 sample yielded the greatest level of compressive strength, substituting 10% of cement with fly ash and 70% of coarse natural aggregates with coarse marble aggregates represents a practical and effective partial solution for replacing natural cementitious materials with marble by-products.

Table 5. Compressive strength (MPa).

Mix designation	**Concrete's Compressive Strength (MPa)**			
	7 days	**14 days**	**28 days**	**56 days**
CF0-CAM0	17.6	21.32	27.94	30.03
CF0-CAM10	17.47	21.84	28.61	30.61
CF0-CAM30	17.95	22.72	30.5	32.78
CF0-CAM50	19.16	23.56	31.10	33.43
CF0-CAM70	21.50	26.60	34.25	36.82
CF0-CAM90	20.97	25.16	31.32	33.51
CF10-CAM0	15.84	19.18	27.60	30.48
CF10-CAM10	15.72	19.43	28.64	30.95
CF10-CAM30	16.16	20.44	30.62	33.15
CF10-CAM50	17.24	21.20	31.85	33.82
CF10-CAM70	19.35	24.20	34.60	37.25
CF10-CAM90	18.87	22.64	31.62	33.90

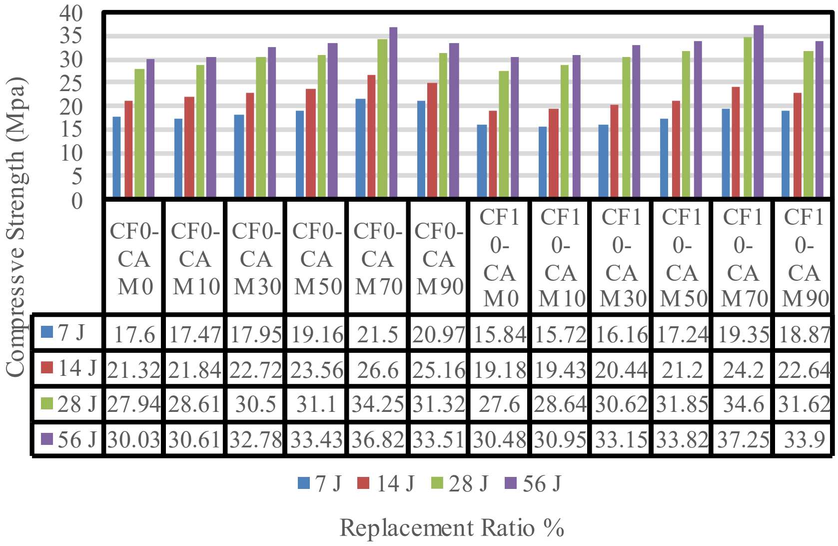

Fig. 6. Concrete's compressive strength variation with replacement.

4.3. Effect of coarse marble aggregates and flay ash on the Schmidt rebound hammer

At 28 days, concrete cube samples were subjected to Schmidt-Hammer tests. Table 6 and Fig. 7 display the rebound numbers for the cement paste, referencing the same data. The findings show that, in comparison to conventional concrete CF0-CAM0, the compressive load resistance increases with the percentage of coarse marble aggregates. Table 6 shows that substituting 10% fly ash for cement and using 70% marble aggregates instead of natural coarse aggregates resulted in the highest compressive load resistance.

However, the rebound numbers of the concrete with marble aggregates dropped when 10% fly ash was added in place of cement. Fly ash's effects on the concrete's characteristics, which alter the surface's texture and structure, are to blame for this decline. Fly ash can, in fact, initially increase the concrete's porosity, which could lower the rebound number. Nevertheless, the concrete's increased strength after 28 days caused the fly ash's surface to harden, which raised the rebound number altogether.

Table 6. Compressive strength and rebound number.

Mix designation	Rebound Number	Compressive Strength (MPa)
CF0-CAM0	36.5	27.94
CF0-CAM10	36.9	28.61
CF0-CAM30	38.1	30.5
CF0-CAM50	38.5	31.10
CF0-CAM70	40.3	34.25
CF0-CAM90	38.6	31.32
CF10-CAM0	36.2	27.60
CF10-CAM10	36.8	28.64
CF10-CAM30	38.2	30.62
CF10-CAM50	38.9	31.85
CF10-CAM70	40.4	34.60
CF10-CAM90	38.8	31.62

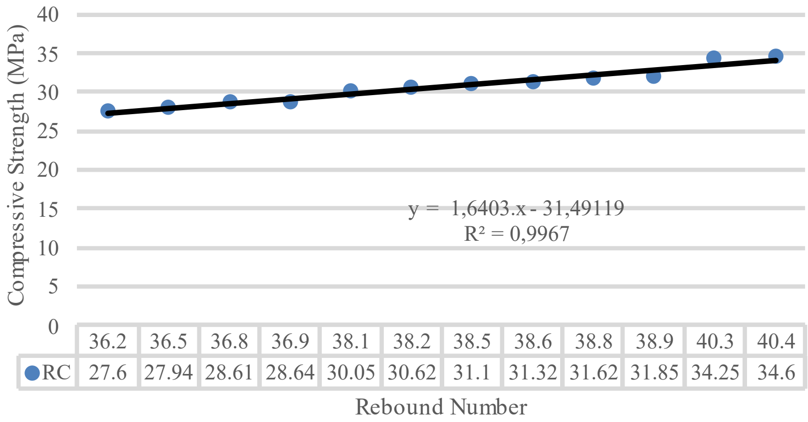

Fig. 7. Rebound number variation with replacement proportion.

The correlation between compressive strength and (R_c) and rebound number (Rn) of concrete containing fly ash and marble coarse aggregate is illustrated in Fig. 7. To obtain data close to reality, a regression analysis using the least squares method, a mathematical concept, was conducted. This approach makes it easier to evaluate the quality of concrete by quantifying the effects of changes in one parameter on the other. Determining this correlation is essential for optimizing concrete formulations and enhancing their mechanical performance, as it enables the rebound number to serve as a reliable indicator of compressive strength. In this case, an Eq. (1) for calculating compressive strength based on the obtained results was established in the following form:

$$R_c = 1{,}6403.Rn - 31{,}9119 \ \ with \ \ R^2 = 0{,}9967 \qquad (1)$$

Where R_c represents the compressive strength of concrete in MPa, Rn is the rebound number measured with the Schmidt hammer, where R is the correlation coefficient derived from this model. Overall, empirical equation findings demonstrated very good compatibility with experimental results, as indicated by the largest error level.

4.4. Impact of coarse marble aggregates and flay ash on the velocity of ultrasonic pulses

A 28-day curing period was used as the reference basis for evaluating the concrete's ultrasonic pulse velocity (UPV) measurements to maintain simplicity in the analysis. A UPV value between 3.5 km/s and 4.5 km/s is generally considered good, indicating adequate density. According to Table 7, which displays the concrete’s ultrasonic pulse velocity values, the concrete exhibits good quality when it falls within the range of 3.45 km/s to 4.36 km/s.

Table 7 shows that adding marble aggregates usually makes both UPV and compressive strength better. This is especially true for the CF0-CAM70 mix, which has a UPV of 4.36 km/s, which is 18.47% higher than the CF0-CAM0 reference mix. Adding 10% fly ash (CF10) lowers the ultrasonic pulse velocity (UPV) slightly because the dry density goes down and the porosity goes up. This is especially true at low marble aggregate concentrations (e.g., CF10-CAM0 with a UPV of 3.45 km/s). But mixes with 50% and 70% marble (CF10-CAM50 and CF10-CAM70) show strong UPV and compressive strength values. For example, CF10-CAM70 has a UPV of 4.14 km/s, which is 20% higher than that of CF10-CAM0.

The reason for this decline is that fly ash concrete has a smaller dry density, which causes the matrix to develop air-filled pores as it cures and dries.

In conclusion, pulse velocity significantly increases when cement is substituted with fly ash and when coarse natural aggregates are substituted with coarse marble aggregates.

Table 7. Compressive strength and UVP.

Mix designation	UPV (Km/s)	Compressive Strength (MPa)
CF0-CAM0	3.68	27.94
CF0-CAM10	3.78	28.61
CF0-CAM30	3.95	30.05
CF0-CAM50	4.06	31.10
CF0-CAM70	4.36	34.25
CF0-CAM90	4.10	31.32
CF10-CAM0	3.45	27.60
CF10-CAM10	3.55	28.64
CF10-CAM30	3.71	30.62
CF10-CAM50	3.85	31.85
CF10-CAM70	4.14	34.60
CF10-CAM90	3.82	31.62

The experimental results were compared with empirical data to evaluate the ultrasonic pulse velocity and compressive strength of concrete containing fly ash and marble coarse aggregates, as shown in Fig. 8.

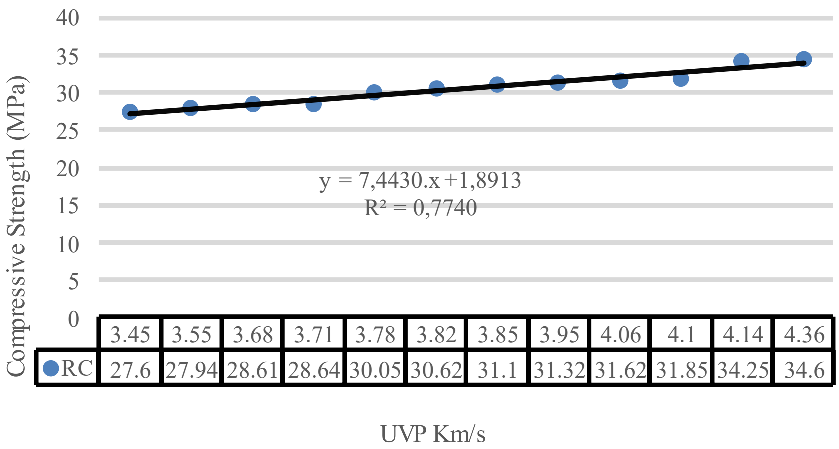

Fig. 8. Ultrasonic pulse velocity variation with replacement proportion.

Subsequently, to obtain data close to reality, a regression analysis using the least squares method, a mathematical concept, was conducted to determine a formula for calculating the compressive strength obtained from the UPV test results. The correlation is represented by:

$$R_c = 7{,}443.upv + 1{,}8913 \quad with \;\; R^2 = 0{,}774 \tag{2}$$

Where R_c represents the compressive strength of concrete in MPa, upv is the velocity of ultrasonic wave propagation in km/s, and R is the correlation coefficient derived from this model. Its value is a measure of how well the function fits the experimental data.

4.5. Rebound number, UVP, and compressive strength relationships

Evaluating concrete properties requires the use of multiple techniques, as variations in the characteristics of concrete can influence test results. This approach helps to reduce potential errors associated with relying on a single method. Therefore, the concrete was analysed simultaneously using the ultrasonic pulse velocity (UPV) method and the Schmidt hammer method. The Son Reb method, a non-destructive technique, is recognized as one of the most commonly used approaches for assessing concrete compressive strength.

The objective of this study is to establish a correlation between concrete compressive strength (dependent variable) and the independent variables, rebound number (Rn) and UPV. Regression statistical analysis has established a linear correlation to estimate the compressive strength of concrete (*Rc*) based on ultrasonic pulse velocity (UPV) and rebound number (Rn). The estimation formula can be found below:

$$R_c = -30{,}528 + 0{,}449.upv + 1{,}559.Rn \quad with \;\; R^2 = 0{,}997 \tag{3}$$

Where R_c represents the compressive strength of concrete in MPa, *upv* is the velocity of ultrasonic wave propagation in km/s, *Rn* is the rebound number measured with the Schmidt hammer and *R* is the correlation coefficient derived from this model.

The correlation coefficient indicates a very strong correlation between the variables, demonstrating that this formula allows for a very accurate estimation of the concrete's compressive strength based on the values of UPV and Rn. Rebound number RN, compressive strength, and correlation curve as shown in Fig. 9.

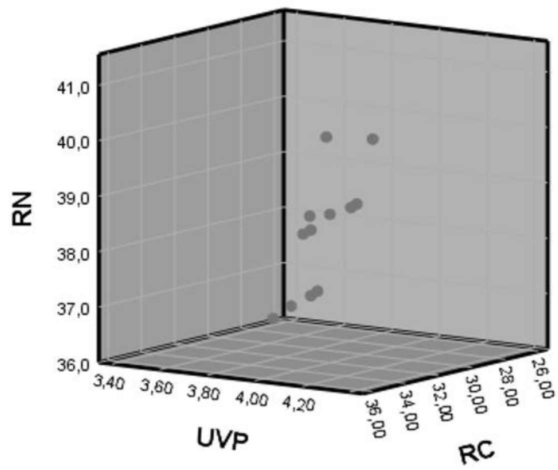

Fig. 9. Rebound number RN, compressive strength, and correlation curve.

5. Challenges of Incorporating Marble Aggregates in Concrete

It is important to take into account any potential restrictions when using marble aggregates in concrete. In contrast to natural aggregates, which are usually rougher, marble has a smooth surface. The marble's smooth texture weakens the mechanical bond between the aggregates and the cement matrix, restricting the adherence of the marble particles to the cement paste. This poor adhesion may cause the concrete's compressive and tensile strengths to decrease, which may impact the concrete's overall performance, especially concerning structural strength and durability.

Furthermore, the extraction and processing of marble can have a substantial environmental impact, even though recycling it for concrete may seem like a good idea. High energy consumption is frequently necessary for marble extraction, which can also have a negative ecological impact locally by degrading the landscape and upsetting nearby ecosystems. To balance the possible ecological advantages of recycling marble against its drawbacks, these effects must be carefully considered.

The durability of concrete with marble aggregates is another crucial consideration. Marble may shorten the lifespan of concrete in harsh environments because it is more vulnerable to chemical and weather attacks than some natural aggregates. Concrete that contains marble aggregates, for instance, might not be as resistant to moisture, freeze-thaw cycles, or acidic or alkaline environments, which could cause material degradation to occur sooner.

Another important factor to take into account is how long concrete with marble aggregates will last. Because marble is more susceptible to weather and chemical attacks than some natural aggregates, it may reduce the lifespan of concrete in harsh environments. For example, marble aggregates may make concrete less resilient to moisture, freeze-thaw cycles, and acidic or alkaline environments, which could accelerate material deterioration.

6. Conclusion

Sustainable practices in the construction industry are increasingly important due to the environmental pressures caused by the depletion of natural resources. As the demand for natural aggregates and cement continues to rise, alternatives such as fly ash for cement and marble coarse aggregates for natural coarse aggregates have gained attention. Our main focus was scientific rather than economic. The research concentrated on the environmental impacts of using recycled materials, such as fly ash and marble aggregates, to reduce dependence on natural resources and carbon dioxide emissions. We assessed how these materials improve the mechanical properties of concrete, particularly its compressive strength and durability, which are essential for the longevity of structures. This methodology aims to promote sustainable construction practices. To validate the impact of adding fly ash and marble residues to concrete, several experiments were conducted. The test results indicated that:

- Slump values of concrete containing 10% fly ash as an alternative to cement and more than 50% marble aggregates exhibit a higher initial slump than normal concrete, as does that containing only marble coarse aggregates instead of natural coarse aggregates.

- 2- After 56 days, the mixture that had 10% fly ash instead of cement and 70% marble coarse aggregates instead of natural coarse aggregates had a 24.04% higher compressive strength than conventional concrete.
- 3-Apart from the CF10-CAM10 and CF10-CAM30 mixtures, all mixes containing fly ash and marble aggregates show normal ultrasonic pulse velocity values, with the CF10-CAM70 mixture exhibiting a peak.
- 4-It is clear that there is a good approximation of the compression strength obtained from the Universal Testing Machine by comparing the compression strength determined using the Schmidt hammer conversion chart.
- 5-The rebound number of the Schmidt hammer, ultrasonic pulse velocity, and compressive strength are all highly correlated when using the combined SonReb method. Here, the rebound number of the Schmidt hammer and the ultrasonic pulse velocity are independent variables.

Abbreviations

ACI	American Concrete Institute
CF	Fly Ash instead of Cement
CSH	Calcium Silicate Hydrate
FA	Fly Ash
MCA	Marble Coarse Aggregate
MPa	Megapascal
R	Correlation coefficient
Rc	Compressive Strength
Rn	Rebound number
UTM	Universal Testing Machine

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