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Original Article

Concrete production using marble powder and marble coarse aggregates: an analysis of mechanical properties and sustainability

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Abstract: The growing demand for concrete driven by infrastructure and urbanization puts pressure on natural resources and harms the ecosystem. Using recycled materials like waste marble powder (WMP) and marble coarse aggregates (MCA) in concrete can address this demand while maintaining quality. This study explores the mechanical properties of eco-friendly concrete with varying levels of marble waste substitution, replacing cement with WMP (0%-10%) and natural aggregates with MCA (10%-90%). A combination of destructive and non-destructive tests, including the Schmidt hammer and ultrasonic velocity tests, was used to assess flexural, compressive, and split tensile strengths. Results showed a 15.78% increase in workability when marble coarse aggregates were added. Compressive strength gained up to 44.02% on day 14 with 10% marble powder and 70% marble aggregates, compared to the control mixture. Split tensile strength improved by 11.02%, 11%, and 10.33% on days 7, 14, and 28, respectively, for mixes with 70% marble aggregates. Ultrasonic pulse velocity ranged from 3.68 km/s to 4.71 km/s, indicating no negative impact on concrete quality. The Schmidt hammer results correlated well with compressive strength from destructive tests. Overall, the study highlights the potential of using marble waste as an effective substitute for natural aggregates in concrete.

Keywords: marble replacement, workability, strength, Schmidt hammer, ultrasonic velocity

1. Introduction

Concrete, a widely utilized composite material, stands as a pivotal structural component in the evolution of global infrastructure. It ranks second only to water in terms of usage, with a worldwide production of around 5.3 billion cubic meters annually [1]. It consists of three primary elements: water, aggregate, and cement. Cement, the primary ingredient in concrete, serves as a binding agent when combined with water and aggregates in its powdered state. The manufacture of concrete reportedly accounts for 8% of the CO_2 emissions worldwide [2], with Portland cement being a primary participant [3,4]. The extraction of all concrete's raw materials, directly or indirectly sourced from the Earth's crust, has heightened global depletion of these resources. Consequently, significant environmental and economic concerns have arisen due to the widespread utilization of concrete [5,6]. This necessitates a complete or partial replacement of cement with an environmentally friendly substance. In this scenario, two objectives were anticipated: the first aims to reduce the CO_2 emissions generated by cement manufacturing, while the second seeks to mitigate environmental effects by utilizing residual industrial materials as fine/coarse aggregates or as alternatives to cement. To reduce CO_2 emissions, one can decrease cement manufacturing by substituting a portion of the cement with residual materials that enhance the characteristics of both hardened and fresh concrete. This would lead to a decrease in manufacturing operations, thereby improving cost and time efficiency while also reducing pollution levels in the environment [7].

Researchers have suggested several waste products from industry and agricultural materials in the last century, such as Rice Husk Ash, Fly Ash, Sewage Sludge Ash, Bagasse Ash, Polyvinyl Chloride Waste Powder (PWP), and Textile Sludge Ash (TSA), capable of partially substituting concrete ingredients. This approach notably preserves natural resources, mitigating their depletion, while also enhancing the economy and sustainability of concrete production [8]. Marble waste is one of these byproducts; it is produced in marble mines when marble is cut [2]. There are two types of marble waste produced as industrial byproducts of the marble industry: marble dust and coarse marble [9].

Within research by Binici et al. [10], 100% of the natural coarse aggregates in concrete were replaced by waste marble while keeping the water-to-cement ratio steady at 0.4 by weight. It was noted that the smooth surface texture and reduced absorption of water of the marble waste made the concrete mixes containing it more workable than the control mixes. Marble waste aggregates were used in place of traditional coarse aggregates in research by Hebhoub et al. [11], maintaining a constant water-to-cement ratio of 0,5. The findings demonstrated that when the replacement rate rose, workability declined. Additionally, all concrete mixes containing marble aggregates showed increases in compressive and tensile strength ranging from 16% to 25% at a replacement rate of 75% by weight. In an investigation conducted by Gencel et al. [12], as a reference, crushed rock was employed, and marble waste was substituted in various proportions for conventional coarse aggregates, including 10%, 20%, and 40%. According to the findings, the concrete mixes' unit weight decreased by 40%. André [13] used coarse marble aggregates in instead of natural aggregates in another study. Over 28 days, a gain in compressive strength was observed with up to 50% substitution. In contrast to the control concrete, compressive strength dropped after 50%. Using leftover marble as coarse aggregates, André et al. [14] conducted a separate study to analyze the characteristics of the concrete produced. A substitution of 20%, 50%, and 100% of marble waste was implemented. For mixes produced with conventional concrete aggregates, there was a decrease in workability at a 50% substitution rate and an increase at a 20% substitution rate. In an investigation carried out by Ceylan et al. [15], it was mentioned that concrete produced using marble in full substitution of traditional aggregates attained the desired average strength at all ages of curing. Additionally, it was stated that waste marble aggregates had a higher Schmidt surface hardness than conventional aggregates and that the ultrasonic velocity values increased. According to Martin et al. [16], coarse aggregates made from residual marble were used to partially replace conventional coarse aggregates in concrete to improve its mechanical properties. Additionally, it was observed that at replacement levels ranging from 20% to 100%, the density decreased slightly by 0.28% to 4.21%, and the workability of the various concrete mixtures increased from 4.16% to 9.34%. Regarding tensile and compressive strength, a slight decrease of 1% to 10.4% and 5.2% to 6.2%, respectively, was reported for replacement levels of 20% to 100%. Throughout the investigation realized by Sudarshan et al. [17,18], 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 coarse aggregates, representing 75% of the total weight, were replaced by marble coarse aggregates. Test findings showed compressive strength like that of traditional concrete. In contrast to traditional concrete, the absorption of water was reduced by 17%. and a 2% increase in abrasion resistance. In their research, Sarath Sunil and Nisha Varghese [19], looked at the feasibility of replacing some coarse aggregate with marble coarse aggregate made. They investigated replacement indices ranging from 0% to 100%. As the marble content was increased up to 50%, it was found that the flexural, tensile, and compressive strengths had all increased. In their research, S. Sahu et al. [20], natural coarse aggregates were substituted with leftover marble aggregates. The study's findings demonstrated that concrete with 10% waste marble substituted in it has strength equivalent to conventional concrete. In their research, Osman et al. [21] replaced natural coarse aggregates (NCA) with recycled marble coarse aggregates (RMCA) in percentages of 50% and 100%. The best workability is obtained when natural aggregates are completely substituted with marble coarse aggregates. Black marble waste aggregates were used in place of natural coarse aggregates by Sowjanya et al. [22] in the following proportions: 0%, 20%, 40%, 60%, 80%, and 100%. According to the study's findings, workability of conventional concrete increased when natural aggregates were substituted with waste black marble aggregates. Compressive strength peaked when 40% of natural coarse aggregates were substituted with waste black marble stone aggregates, and water absorption by the concrete was nearly absent when natural aggregates were replaced with waste black marble stone aggregates.

2. Research relevance

Reducing reliance on natural resources and minimizing environmental degradation are the main goals of this study. From this perspective, our study focuses on conducting a thorough of the characteristics of concrete resulting from partially replacing marble powder with cement and coarse natural aggregates with coarse marble aggregates. The percentage of marble powder added to concrete in place of cement was 10%, while natural coarse aggregates were replaced with marble coarse aggregates at rates ranging from 10% to 90%, increasing gradually by 20%. Concrete samples produced with these modifications are evaluated for workability, Schmidt rebound hammer index, split tensile, flexural strength, ultrasonic pulse velocity, and compressive strength. By closely examining the consequences of these changes on the composition and performance of concrete, the feasibility and environmental benefits of this alternative approach are aimed to be assessed.

3. Experimental study

3.1. Characterization of materials

With a minimum clinker content of 65%, Portland cement CPJ 45 was selected as the binder for this project to formulate concrete. The remaining materials consisted of additives such as fly ash, pozzolans, and fillers provided by Holcim and complying with the Moroccan specifications NM10.1.004 [23]. The concrete was mixed using water for drinking supplied by Oujda's Autonomous Intercommunal Water and Electricity Distributing Agency (RADEEO). This water meets the physical and chemical standards of NM 10.1.353 [24]. For this project, Oujda region natural sand was used. It was almost devoid of impurities, with a specific gravity of 2.68, a 2.5% water absorption, and a 2.85 fineness modulus. Its smooth, spherical, rectangular shape provides good workability. To manage the water content of the concrete, the sand was dried for an entire day at room temperature. The largest sand's size was 4.75 mm. The NF EN 12620 [25] standard was followed for conducting the sand tests. In this investigation, two varieties of crushed coarse stone aggregates, G1 with Sieve Range 5-11(mm) and G2 with 11-20(mm), with specific gravity of 2.70 and 2.72 respectively, and water absorption of 1.48% and 1.50% respectively, were used as stated by the NF P-18-560 [26] standard. As an auxiliary material of the process of shaping and cutting, marble companies provided marble dust in the form of powder and Coarse Aggregate. Marble waste used was crushed into crusher in order to obtain a size ranging from 5 to 20 mm. The Waste Marble Powder has a Fineness Blaine of 3320 m^2/kg and a specific gravity of 2.71. The Marble Coarse Aggregate has a specific gravity of 2.73 and water absorption of 0.50%. Table 1 displays the initial and final setting times, consistency, the sand's specific gravity, the coarse gravel's specific gravity, the Fineness Blaine and absorption of water results. Table 2 displays natural aggregate's chemical constituents. Figure 1 displays the size of the particles analyses of the different materials utilized.

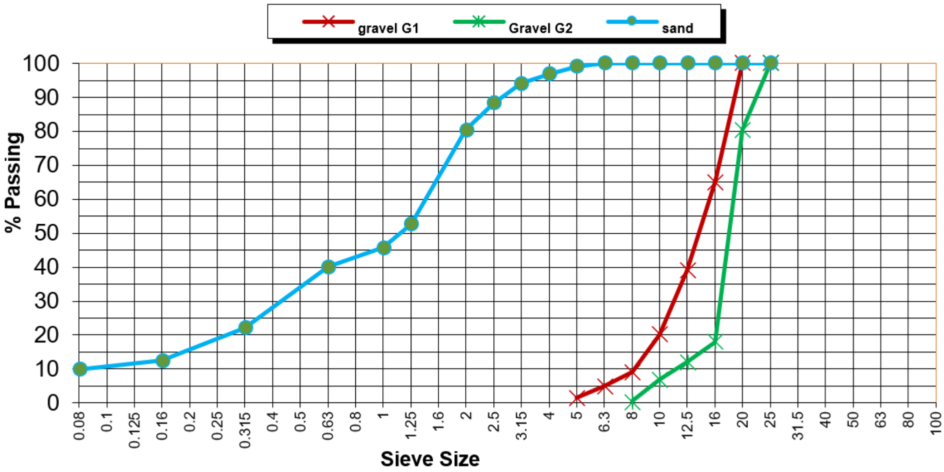

Fig. 1. Distribution of sand, gravel G1, and gravel G2 particle sizes. *Source:* own study

To get rid of extra water, the trash was first air-dried and then oven-dried. There is a significant specific surface area in the marble powder, which suggests that adding it to mortars and concretes should increase their cohesiveness. The physical characteristics of

Cement, WMP, sand, coarse aggregate G1, G2, and MCA are presented in Tab. 1 The chemistry constitution of marble dust and Portland cement CPJ 45 was assessed by the use of X-ray fluorescence (XRF) analysis, according to Tab. 2. The marble powder X-ray diffraction (XRD) spectrum is seen in Fig. 2.

Table 1. Physical characteristics of Cement, WMP, sand, coarse aggregate G1, G2, and MCA. *Source:* own study

Property	Cement	WMP	Sand	G1	G2	MCA
Specific gravity	3.15	2.71	2.68	2.70	2.72	2.73
Water absorption %			2.50	1.48	1.50	0.5
Consistency (%)	29					
Initial setting time (min)	180					
Final setting time (min)	210					
Fineness Blaine (cm^2/gm)	3100	3320				

Table 2. Chemical constitution of residual marble powder and cement. *Source:* own study

Constituent (%)	Cement (%) by mass	WMP (%) by mass	Sand (%) by mass
CaO	60.06	47.71	5.58
SiO2	20.90	6.69	77.40
Fe2O3	3.90	0.82	2.66
AL2O3	5.85	2.16	8.18
MgO	1.85	1.52	0.77
K2O	2.14	0.25	0.25
TiO2	0.32	0.06	0.005
SO3	2.35	0.44	0.018
LOI	21.84	39.83	……..

WMP: waste marble powder

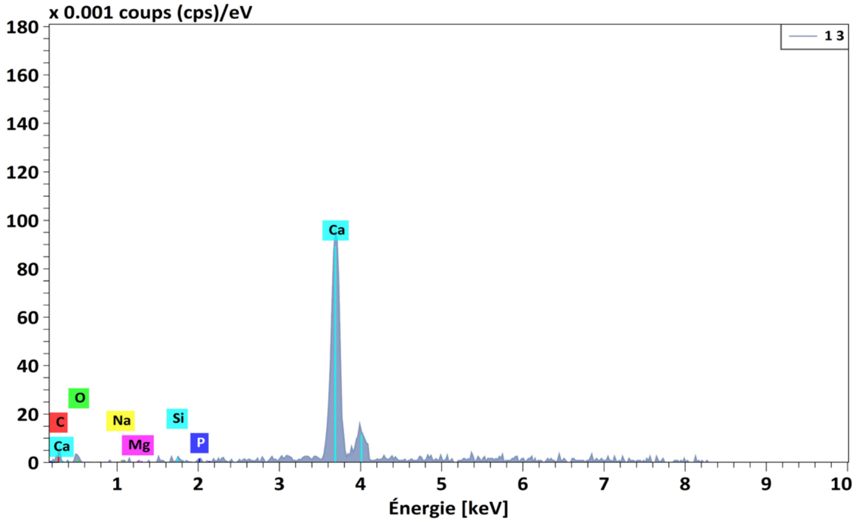

Fig. 2. X-ray diffraction spectrum of marble powder. *Source:* own study

To evaluate the impact of substituting waste marble powder for a part of the cement and marble coarse aggregate for a part of natural coarse aggregate on concrete performance, a 0.5 water-to-cement ratio was used to produce 12 mixtures for every test specimen. The percentage of marble powder added to concrete in place of cement was 10%, while natural coarse aggregates are changed out for marble coarse aggregates at rates ranging from 10% to 90%, increasing gradually by 20%. The mixture ratios of concrete are listed in Tab. 3. The symbol CM indicates marble powder used in place of cement, and CAM indicates marble aggregates instead of natural aggregates. For example, CM10-CAM30 refers to the mixture in which Marble powder is employed in lieu of 10% of the cement and 30% of the natural aggregates are replaced with alternative aggregates. The Dreux-Gorisse model was applied to carry out the concrete design.

Table 3. Mixture proportions with w/c=0,5. *Source:* own study

Mix identification	WMP (%)	MCA (%)	Water (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	G1 (kg/m^3)	G2 (kg/m^3)	WMP (kg/m^3)	MCA (kg/m^3)
CM0-CAM0	0	0	175	350	763	327	833	0	0
CM0-CAM10	0	10	175	350	763	294	750	0	116
CM0-CAM30	0	30	175	350	763	229	583	0	348
CM0-CAM50	0	50	175	350	763	164	416	0	580
CM0-CAM70	0	70	175	350	763	98	250	0	812
CM0-CAM90	0	90	175	350	763	33	83	0	1044
CM10-CAM0	10	0	175	315	763	327	833	35	0
CM10-CAM10	10	10	175	315	763	294	750	35	116
CM10-CAM30	10	30	175	315	763	229	583	35	348
CM10-CAM50	10	50	175	315	763	164	416	35	580
CM10-CAM70	10	70	175	315	763	98	250	35	812
CM10-CAM90	10	90	175	315	763	33	83	35	1044

3.2. Test parameters

The study's experimental program took place at two locations: the testing building materials laboratory within the Oujda Faculty of Science and the LABNORVIDA testing laboratory in Oujda. Concrete mixes were meticulously prepared using a 125-liter capacity pan mixer. First, the mixer was filled with coarse aggregates, followed by the addition of fine aggregates. A small amount of water, taken from the total calculated quantity, was also added. The blend of cement and marble dust was subsequently added before incorporating the remaining water. The mixer was left running until a homogeneous mixture was achieved.

3.2.1. Workability

The effect of partially substituting marble powder for cement and Marble Coarse Aggregate for Natural Coarse Aggregates on the regularity of freshly mixed concrete mixes was studied using the slump cone test in compliance with NF EN 12350-2 [27]. The slump cone had a standard size, measuring 300 mm in height, 200 mm in bottom diameter, and 100 mm in top diameter. Workability was assessed by conducting slump tests on all the mixtures and measuring the slump values for various concrete blends. Marble Coarse Aggregates was used at rates of 10%, 30%, 50%, 70%, and 90% in place of some of Natural Coarse Aggregates, and 10% of marble powder in place of cement.

3.2.2. *Compressive, split tensile and flexural strength*

Compressive strength is crucial for assessing the structural capacity of concrete in buildings. To find out the concrete's compressive strength, concrete cubes measuring 150 mm on each side are cast. According to NF EN 12390-3 [28], compressive strength is measured at curing ages of day7, day 14, and day 28 using the Universal Testing Machine (Fig. 3). The samples were cured under 100% relative humidity and a constant ambient temperature of 27 ± 2°C with water.

Cylinders, measuring 300 mm in height and 150 mm in diameter, are created. to gauge the concrete's split tensile strength. Following the guidelines of NF EN 12390-6 [29], the tensile strength is assessed at curing ages of day 7, day 14, and day 28.

To assess the concrete's flexural strength of, concrete prisms of 500 mm by 100 mm by 100 mm were cast. As per NF EN 12390-5 [30], flexural strength is determined after day 7, day 14, and day 28 of the treatment.

Fig. 3. Compressive universal testing machine

3.2.3. *Ultrasonic pulse velocity*

Concrete quality can be evaluated in situ using a non-destructive technique called ultrasonic pulse velocity testing. The NF EN 12504-4 [31] standard procedure for ultrasonic testing is followed. The test was conducted using a voltage of 500 V and a frequency of 54 kHz. The gadget is shown in Fig. 4. An ultrasonic pulse sending and receiving processor unit is part of the gadget, and it also measures the interval between the two processes. The sound energy is transferred via two probes on the apparatus. The pulse flow rate is determined by the time interval between these two acts: the probe that is sent into the concrete emits sound energy, and the probe that is received receives this energy. The pulse flow rate in this study is determined via opposite surfaces, as Fig. 4 illustrates. Concrete cube specimens are subjected to ultrasonic pulse velocity tests after 28 days.

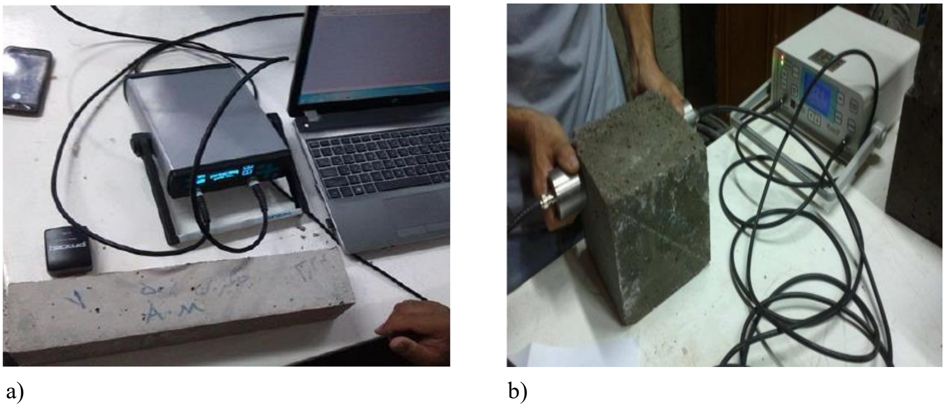
a) b)

Fig. 4. Ultrasonic pulse velocity testing procedure: a – sonic inspection device, b – direct transparency measurements

3.2.4. *Schmidt Rebound Hammer*

By measuring the rebound of a spring-driven hammer that strikes the concrete surface, the Schmidt Rebound Hammer (Fig. 5) is an instrument used to determine the concretes compressive strength. This non-destructive control technique yields a concrete strength estimate compliant with NF EN 12504-2 [32]. The rebound hammer readings are correlated to concrete compressive strength using conversion charts provided by the manufacturer. These charts are based on extensive testing and correlations between rebound values and actual concrete compressive strength.

Fig. 5. Schmidt rebound hammer

4. Results and conversational analysis

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

The workability of concrete blends was assessed through the incorporation of marble powder instead of cement at a 10% ratio, and by substituting coarse natural aggregates with marble coarse aggregates ranging from 10% to 90%, alongside supplementary cementitious material. These measurements were then juxtaposed with those obtained from conventional concrete. The replacement rates and slump values of the mixtures are detailed in Tab. 4. The slump values of fresh concrete varied between 50 and 66 mm, which fell within the target slump range of S2(Plastic concrete) based on the norm NF EN 12350–2 [29]. Notably, an increase in slump was observed in mixtures containing marble coarse aggregates compared to traditional concrete. This is explained by the smooth surfaces of the marble coarse aggregates, which effectively diminish friction between particles, thus facilitating the flow and mobility of the mixture. Another aspect contributing to the improvement in workability during the progressive substitution of marble coarse aggregates for natural coarse aggregates is the superior shape index of marble coarse aggregates compared to the natural coarse aggregates. Furthermore, Tab. 4, reveals that Slump values of concrete compositions with marble coarse aggregates were higher than those of conventional concrete, though they were slightly lower than those of mixtures with 10% marble powder in place of cement and marble coarse aggregates. Additional cementitious materials, specifically those possessing a large specific surface area like marble powder as opposed to CPJ cement, necessitate a relatively higher water content, resulting in a decrease in slump. The same observations were made by Hebhoub [11], Aliabdo [33], Ashish [34], and Vardhan [35].

Table 4. Slump values. *Source:* own study

Mix designation	Slump (mm)
CM0-CAM0	57
CM0-CAM10	58
CM0-CAM30	58
CM0-CAM50	62
CM0-CAM70	65
CM0-CAM90	66
CM10-CAM0	50
CM10-CAM10	51
CM10-CAM30	51
CM10-CAM50	55
CM10-CAM70	57
CM10-CAM90	58

4.2. Marble powder's impact on the compressive strength

Tests of compressive strength were carried out on concrete samples. During the process, the specimens underwent water curing. Before analysing each concrete specimen at days 7, 14, and 28, samples were given a full day to dry. Three specimens were used to obtain the average result. Utilizing the universal testing machine, compressive strength results were acquired. Table 5 displays the compressive strength values for each test specimen. We observe that the samples' compressive strength, where marble powder is used in place of 10% of cement and natural coarse aggregates by marble coarse aggregates, undergoes a progressive increase at the ages studied for substitutions ranging from 10% to 70%. A slight decrease is noticed for the case of 90%, while still remaining higher than the compressive strength of conventional concrete. At Day 7, 14, and 28, improvements of 22.15%, 24.76%, and 22.58% were noticed in the samples' compressive strength in which 70% of natural coarse aggregates had been substituted for marble coarse aggregates compared to the conventional concrete. As marble powder is used in place of 10% cement, along with the replacement of 70% of natural aggregates with marble aggregates, demonstrates an enhancement in compressive strength of approximately 40.96%, 44.02%, and 38.33% on days 7, 14, and 28. The early increase in compressive strength is indicative of the existence of fine WMP fragments filling the pores and altering the properties of the transition area enveloping aggregates.

Given that the CM10-CAM70 sample yielded the greatest level of compressive strength, substituting 10% of cement with marble powder and 70% of natural aggregates with marble aggregates represents a practical and effective partial solution for replacing natural cementitious materials with marble by-products.

Table 5. Compressive strength (MPa). *Source:* own study

Mix designation	Concrete's Compressive Strength (MPa)		
	Day 7	Day 14	Day 28
CM0-CAM0	17.60	21.32	27.94
CM0-CAM10	17.47	21.84	28.61
CM0-CAM30	17.95	22.72	30.5
CM0-CAM50	19.16	23.56	31.10
CM0-CAM70	21.50	26.60	34.25
CM0-CAM90	20.97	25.16	31.32
CM10-CAM0	21.56	25.22	32.96
CM10-CAM10	21.96	26.57	33.88
CM10-CAM30	22.31	27.08	34.93
CM10-CAM50	23.42	28.10	35.95
CM10-CAM70	24.81	30.92	38.65
CM10-CAM90	23.87	28.96	36.28

4.3. Marble powder's impact on the split tensile strength

The specimens are tested using a universal testing machine (UTM) at days 7, 14, and 28. Table 6 shows the split tensile strength of mixtures were the percentage of marble powder added to concrete in place of cement was 0% and 10%, while natural coarse aggregates are changed out for marble coarse aggregates at rates ranging from 10% to 90%, increasing gradually by 20%. It is observed that the Split Tensile Strength of the samples, in which cement has been changed by marble powder and coarse natural aggregates by coarse marble aggregates, undergoes a progressive increase at the ages studied for substitutions of natural aggregates with marble aggregates ranging from 10% to 70%. A slight decrease is noticed for the case of 90%, while still remaining higher than the compressive strength of conventional concrete. At Day 7, 14, and 28, improvements of 11.02, 11%, and 10.33% were noted in the Split Tensile strength of samples in which 70% of natural coarse aggregates had been substituted for marble coarse aggregates in contrast to traditional concrete. As a substitute of 10% of cement with powdered marble, along with the substitute of 70% of natural coarse gravel with marble coarse gravel, demonstrates an enhancement in Split Tensile strength of approximately 29.38%, 55.9%, and 29.05% on days 7, 14, and 28. This partial replacement of natural cementitious materials with marble by-products is feasible and effective, since the CM10-CAM70 sample produced the greatest level of Split Tensile strength when marble powder was used in place of 10% cement and 70% of natural aggregates with marble aggregates.

Table 6. Split tensile strength (MPa). *Source:* own study

Mix designation	Concrete's Split Tensile Strength (MPa)		
	Day 7	Day 14	Day 28
CM0-CAM0	2.45	2.54	3.58
CM0-CAM10	2.59	2.69	3.79
CM0-CAM30	2.62	2.71	3.82
CM0-CAM50	2.65	2.74	3.87
CM0-CAM70	2.72	2.82	3.95
CM0-CAM90	2.66	2.76	3.90
CM10-CAM0	2.86	3.58	4.17
CM10-CAM10	3.02	3.77	4.41
CM10-CAM30	3.05	3.81	4.45
CM10-CAM50	3.09	3.86	4.51
CM10-CAM70	3.17	3.96	4.62
CM10-CAM90	3.08	3.84	4.45

To assess the split tensile strength and Compressive strength of concrete incorporating marble powder and marble coarse aggregate, experimental findings were compared with empirical data, as depicted in Fig. 6.

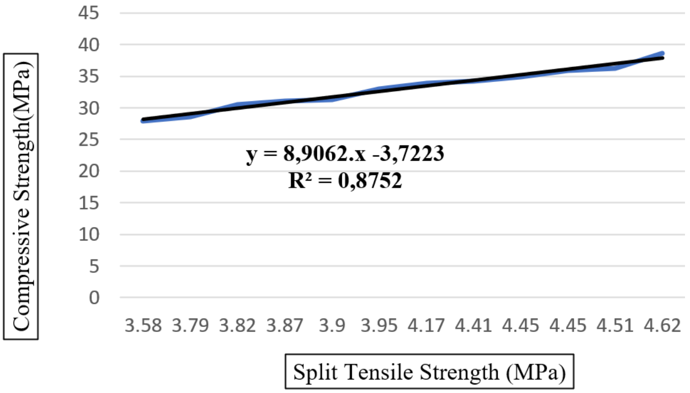

Fig. 6. Relationship between split tensile strength and compressive strength. *Source:* own study

The empirical relationship between compression strength f'_c and splitting tensile strength (f_t) of concrete can vary depending on specifications and standards, but a commonly used formula is as follows: $f_t = k\sqrt{f'_c}$, where k is a coefficient that generally varies between 0.5 and 0.75 according to different standards' specifications and test conditions. In the case of our research, the above-mentioned relationship holds true with k close to 0.7.

4.4. Marble powder's impact on the flexural strength

The samples are examined utilizing a universal testing machine (UTM) at day 7, day 14, and day 28. Table 7 displays the flexural strength values of mixtures were the percentage of marble powder added to concrete in place of cement was 0% and 10%, while natural coarse aggregates are replaced with marble coarse aggregates at rates ranging from 10% to 90%, increasing gradually by 20%. The replacement of marble waste at the curing ages had a favorable effect on the specimens' flexural strength, with the maximum flexural strength observed for concrete CM0-CAM70.

Table 7. Flexural strength (MPa). *Source:* own study

Mix designation	Concrete's Flexural Strength (MPa)		
	Day 7	Day 14	Day 28
CM0-CAM0	3.23	3.48	4.21
CM0-CAM10	3.42	3.69	4.46
CM0-CAM30	3.47	3.74	4.53
CM0-CAM50	3.51	3.79	4.55
CM0-CAM70	3.59	3.87	4.68
CM0-CAM90	3.14	3.39	4.06
CM10-CAM0	3.47	3.74	4.49
CM10-CAM10	3.67	3.96	4.75
CM10-CAM30	3.73	4.01	4.85
CM10-CAM50	3.78	4.08	4.90
CM10-CAM70	3.85	4.16	5.03
CM10-CAM90	3.35	3.55	4.19

To assess the flexural strength and Compressive strength of concrete incorporating marble powder and marble coarse aggregate, experimental findings were compared with empirical data, as depicted in Fig. 7.

Depending on standards and specifications, the empirical relationship between concrete's flexural (f_f) and compressive strengths (f_c) can change. A typical formula is: $f_f=k\sqrt{f'_c}$, where k is a coefficient that generally varies between 0.7 and 0.8 according to different standards' specifications and test conditions. The relationship stated above holds true in the case of our research, with k being close to 0.78.

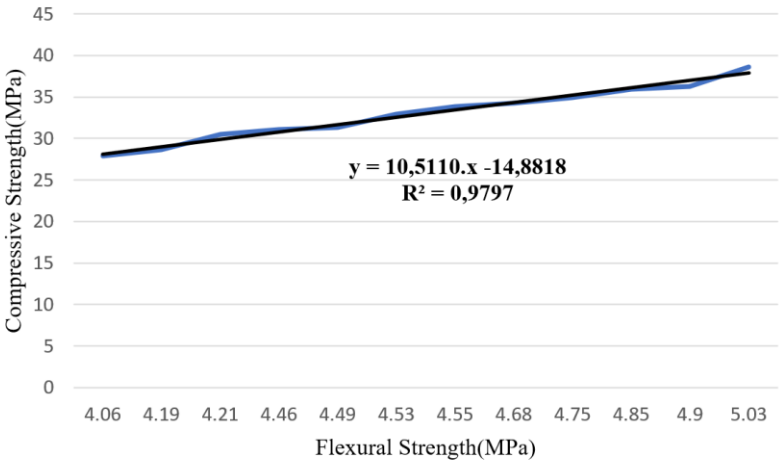

Fig. 7. Relationship between flexural strength and compressive strength. *Source:* own study

4.5. Marble powder's impact on the velocity of ultrasonic pulses

UPV tests on concrete cube samples are performed at 28 days. Table 8 and Figure 8, present the UPV results of the cement paste. It's crucial to remember that all concretes containing marble waste show a normal velocity. The quality of the concrete is not affected when marble powder is used instead of cement and marble coarse aggregates are used instead of natural coarse aggregates. The velocity of ultrasonic pulses increased by 18.47%, 27.98%, 11.41%, and 25.27% for concrete mixtures CM0-CAM70, CM10-CAM70, CM0-CAM90, and CM10-CAM90, respectively, compared to the values of the control mixture CM0-CAM0. Additionally, the maximum quality of concrete was achieved with 10% utilization of marble powder and 70% utilization of marble coarse aggregates. In conclusion, pulse velocity significantly increases when cement is substituted with marble powder and when coarse natural aggregates are substituted with coarse marble aggregates.

Table 8. Compressive strength and UVP. *Source:* own study

Mix designation	UPV (Km/s)	Compressive Strength (MPa)
CM0-CAM0	3.68	27.94
CM0-CAM10	3.78	28.61
CM0-CAM30	3.95	30.50
CM0-CAM50	4.06	31.10
CM0-CAM70	4.36	34.25
CM0-CAM90	4.10	31.32
CM10-CAM0	4.32	32.96
CM10-CAM10	4.45	33.88
CM10-CAM30	4.57	34.93
CM10-CAM50	4.69	35.95
CM10-CAM70	4.71	38.65
CM10-CAM90	4.61	36.28

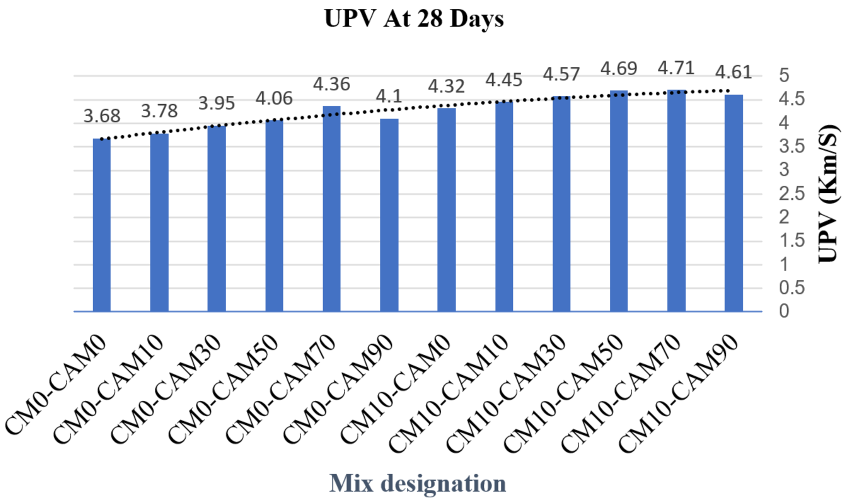

Fig. 8. Ultrasonic pulse velocity variation with replacement proportion. *Source:* own study

To assess the Ultrasonic Pulse velocity and Compressive strength of concrete incorporating marble powder and marble coarse aggregate, experimental findings were compared with empirical data, as depicted in Fig. 9.

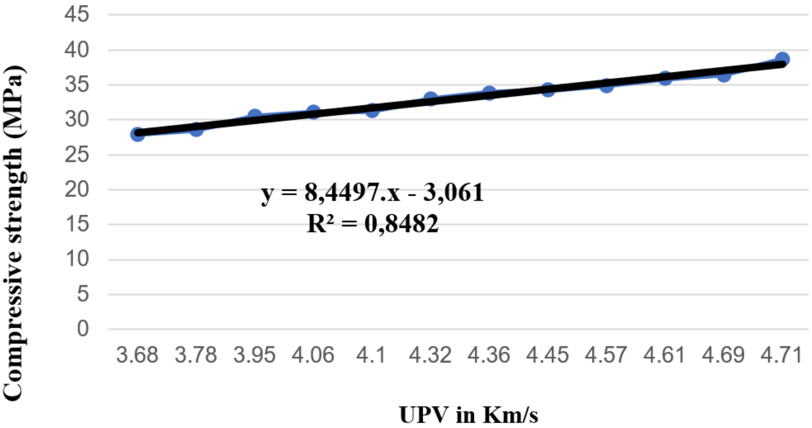

Fig. 9. Ultrasonic Pulse velocity and Compressive strength and relationship. Source: own study

In order to obtain data close to reality, an analysis of regression applying the method of least squares, a mathematical concept, was conducted to examine the correlation between compressive strength and the rebound number obtained from the Schmidt Hammer test results. In this case, an equation for calculating compressive strength based on the obtained results was established in the following form:

$$Rc = 8.4497.\ (uvp) - 3.061 \quad \text{with } R^2=0.8482 \tag{1}$$

4.6. Effect of marble powder on the Schmidt Rebound Hammer

Schmidt Hammer tests on concrete cube specimens are conducted at 28 days. Table 9, and Figure 10, present the Rebound Number results of the cement paste.The examination findings indicated that as the proportion of marble waste increased, there was a corresponding rise in resistance to compressive loads when compared to conventional concrete CM0-CAM0. Likewise, the highest resistance to compressive loads was observed when powdered marble served as a cement substitute at a rate of 10%, and marble aggregates were employed at a rate of 70% instead of natural aggregates, as depicted in Tab. 9.

Table 9. Compressive strength and Rebound Number. *Source:* own study

Mix designation	Rebound Number	Compressive Strength (MPa)
CM0-CAM0	25.38	27.94
CM0-CAM10	26	28.61
CM0-CAM30	27.3	30.5
CM0-CAM50	28.25	31.10
CM0-CAM70	30.65	34.25
CM0-CAM90	28.45	31.32
CM10-CAM0	29.5	32.96

Mix designation	Rebound Number	Compressive Strength (MPa)
CM10-CAM10	30.31	33.88
CM10-CAM30	31.26	34.93
CM10-CAM50	32.18	35.95
CM10-CAM70	34.6	38.65
CM10-CAM90	32.44	36.28

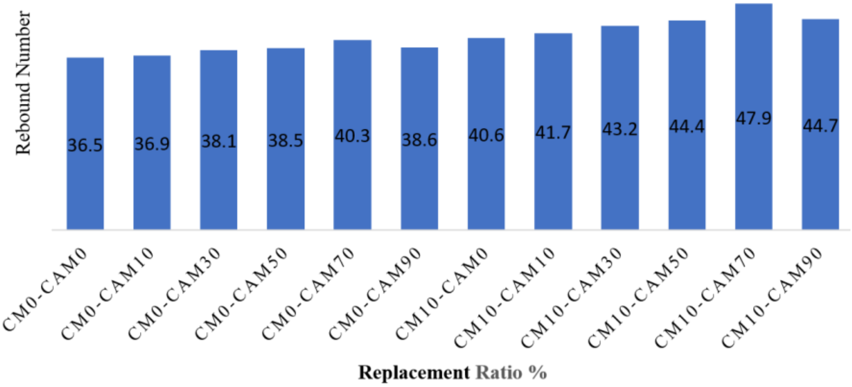

Fig. 10. Rebound number variation with replacement proportion. *Source:* own study

An analysis of regression applying the method of least squares, a mathematical concept, was also employed to examine the correlation between compressive strength and Schmidt Hammer test results, aiming to establish an equation for computing compressive strength based on the obtained results. The correlation is illustrated in Fig. 11 and represented by the equation:

$$Rc = 0.9004\,(Rn) - 3.8262 \quad \text{with } R^2 = 0.9498 \qquad (2)$$

Overall, empirical equation findings demonstrated excellent congruence with findings from experiments, as indicated by the correlation coefficient R^2 which is close to 1

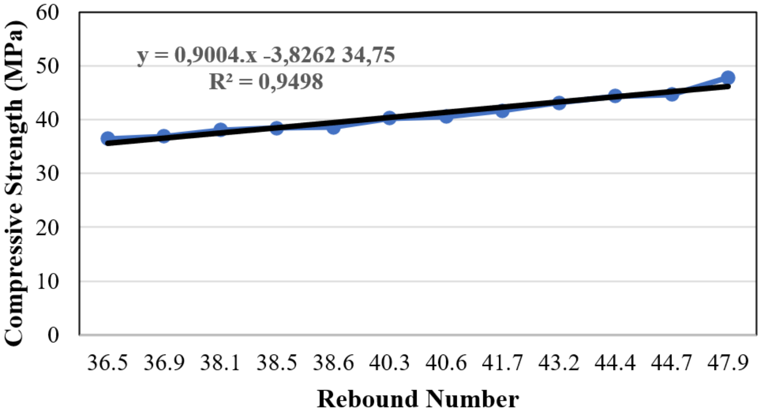

Fig. 11. Connectivity between rebound number and compressive strength. *Source:* own study

4.7. Rebound Number, UVP, and Compressive Strength Relationships

Examining and assessing the necessary properties would require more than one technique, especially when changes to the concrete's characteristics affect test findings Neville [20]. Therefore, by evaluating concrete using both methods simultaneously, errors resulting from relying solely on one method are reduced. The Son Reb method is widely regarded as the non-destructive method most often utilized for evaluating concrete's compressive strength. The principal aim of this paragraph is to set up a correlation between the dependent variable (concrete compressive strength) and the independent variables (rebound number (Rn) and ultrasonic pulse velocity (UPV)), and contrast the results with the strength of samples measured by the universal machine test. A statistical analysis is conducted, and using a combined method, an estimation of the concrete's compressive strength is derived from the following formula presented in Fig. 12:

$$R_C = 4.712\,(UVP) + 0.457(Rn) - 5.813 \quad \text{with } R^2=0.99 \tag{3}$$

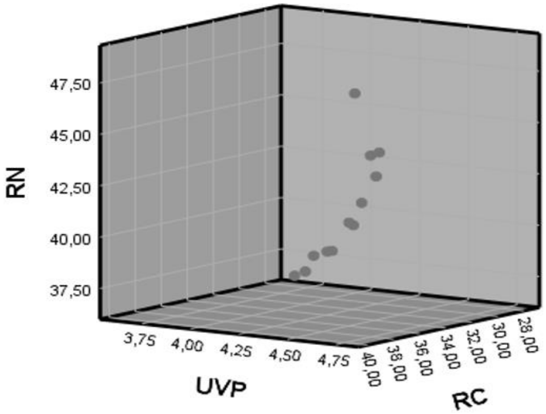

Fig. 12. Rebound number RN, Compressive strength, and UPV correlation curve. *Source:* own study

Given that the $R^2 = 0.99$ is very near to 1, this linear adjustment model between the three variables can be accepted.

5. Conclusion

Research on using marble waste instead of natural aggregates in concrete has revealed a significant knowledge gap regarding sustainable construction materials. Previous studies have considered other options, but have not thoroughly studied the combined effects of marble powder and coarse aggregates.

This study aimed to provide a comprehensive overview of the use of marble waste by evaluating the impact of substituting natural coarse aggregates with marble powder (varying from 0% to 10% of the cement) and marble coarse aggregates (varying from 10% to 90% of the aggregates). The experiment showed that compared to the control mix, the concrete's workability was up to 15.78 percent better after adding marble coarse particles. The compressive strength significantly increased, particularly on day 14, with gains of up to 44.02%, when we replaced 10% of the cement with marble powder and 70% of the natural aggregates with marble aggregates. On days 7, 14, and 28, the split tensile strength of samples that included 70% marble aggregates instead of typical concrete improved by 11.02%, 11%, and 10.33%, respectively.

All mixes showed ultrasonic pulse velocities between 3.68 and 4.71 km/s, indicating that the additions did not affect the concrete. There was a good link between the compressive strength found during the destructive test using the universal testing machine and that found using the conversion chart provided by the Schmidt hammer manufacturer. This was shown by the rebound number that the hammer measured.

These findings provide a viable substitute for traditional materials, showcasing the innovative nature of this technique. Using marble waste and other industrial by-products in concrete improves its characteristics and helps with waste management in an eco-friendly way. This study adds to the growing body of evidence that optimizes the use of substitute materials to improve concrete performance while delivering substantial environmental benefits, as compared to previous research in the same vein.

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