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INVESTIGATION OF MECHANICAL CHARACTERISTICS AND SUSTAINABLE PRACTICES IN CONCRETE INCORPORATING RECYCLED MARBLE WASTE

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ABSTRACT

Due to the rapid expansion of infrastructure, urbanization, and industry, there is a constant need for concrete worldwide. However, the expansion of the concrete sector increases pressure on natural resources, endangering the balance of the ecosystem. Thus, it would be advantageous to meet current concrete needs without reducing production quality by incorporating recycled materials into concrete mixes. In this work, we investigate the mechanical characteristics of environmentally friendly concrete using recycled marble powder (WMP) partially replacing cement and marble coarse aggregates (MCA) as an alternative to natural coarse aggregates. The qualities of the concrete were evaluated using a combination of destructive and non-destructive testing techniques. In this study, three series of mixes were prepared. The first series (S1) is composed of 100% natural coarse aggregates. In the second series (S2), 50% of the natural coarse aggregates are substituted for marble coarse aggregates, while the third series (S3) is composed of 100% marble coarse aggregates. In each of the three series, Marble powder was used in place of cement at a percentage ranging from 5% to 20%, increasing by 2.5%. Concrete mixes were developed and evaluated with different levels of marble waste substitution to compare their compressive strengths and workability to those of traditional concrete made from 100% natural aggregates. Simultaneously, the strength characteristics were measured using the Schmidt hammer and ultrasonic velocity tests. As was mentioned, in the three series, when Cement is replaced with marble powder, the slump decreases, even though the incorporation of marble coarse aggregates tends to increase this workability, while the compressive strength shows an increase of 28.66% and 31.63% compared to the control mix for 50% and 100% substitute of natural coarse aggregates with marble coarse aggregates, respectively. It is also noteworthy that concrete containing marble waste exhibits normal ultrasonic velocity. For concrete mixtures of series (S1), (S2), and (S3), respectively, the velocity of ultrasonic pulses increased by 18.20%, 27.44%, and 27.98%, while the Schmidt Rebound Number increased by 10.13%, 14.52%, and 21.37%, respectively, in contrast to the values of the control mixture. Additionally, the reliability of results from the universal testing machine (UTM) was validated through correlation analysis of compressive strength measurements obtained by various methods. The study's findings are intriguing and underscore the potential of employing marble waste as an alternative to natural aggregates.

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

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1. INTRODUCTION

One common composite material that is essential to the development of the world's infrastructure is concrete. Approximately 5.3 billion cubic meters are produced worldwide each year. It is the second most used resource after water (Ullah K. *et al* 2022). Water, aggregate, and cement are its three main components. When mixed with water and powdered aggregates, cement, the main component of concrete, acts as a binding agent. According to reports, 8% of the CO2 emissions in the world are caused by the production of concrete (Aruntas H. Y. *et al* 2010), with Portland cement being a major contributor (Anwar A. *et al.,* 2015), (Jang J.G. and H.K. Lee 2016). The worldwide depletion of these resources has been accelerated by the extraction of all raw materials used in concrete, whether they are derived directly or indirectly from the Earth's crust. As a result of the extensive use of concrete, serious environmental and financial issues have emerged (Rashad A.M 2013), (Sankh A.C. *et al* 2014). This means that an environmentally friendly material must be used in place of cement, either entirely or in part. In this case, we expect two goals: the first is to lower the CO_2 emissions that come from the production of cement, and the second is to lessen the impact on the environment by using leftover industrial materials as fine- or coarse-aggregates or as cement substitutes.

In the past century, scientists have proposed a variety of waste products from agriculture and industry, including Textile Sludge Ash (TSA), Rice Husk Ash, Fly Ash, Sewage Sludge Ash, Bagasse Ash, and Polyvinyl Chloride Waste Powder (PWP), which can partially replace the ingredients in concrete. Not only does this method improve the economy and sustainability of concrete production, but it also significantly reduces the loss of natural resources (Arulmoly B. *et al* 2021). These byproducts include marble waste, which is created during the cutting of marble in marble mines (Aruntas H. Y. *et al* 2010). As industrial byproducts of the marble industry, marble dust and coarse marble are the two types of waste that are produced (Akbulut S.K. 2007).

As found in the research by Shirule (2012), the incorporation of 10% marble dust into cement increased the compressive strength after 28 days by up to 17%, and by 11.5% for the tensile strength. Shelke (2012) investigated how incorporating marble dust in specific ratios to cement impacted concrete strength. The findings demonstrated that the most favorable compressive strengths at both 7 and 28 days resulted from including 8% recycled marble dust and 8% silica fume in the cement.

As noted by Soliman (2013), there was a maximum increase in compressive strength of 24.56% at 28 days when 5% of the Marble powder was used in place of cement in the nominal mix. However, the strength decreased when marble powder was included in the nominal concrete mixture instead of cement. The splitting tensile strength was reduced by 47%, and the compressive strength at 28 days decreased by 26% compared to a 20% replacement.

Aliabdo (2014) manufactured concrete by substituting marble dust waste at rates of 5%, 7.5%, 10%, and 15% for both sand and cement separately. Their findings indicated that incorporating 15% marble powder showed no significant alteration in ultrasonic pulse velocity compared to scenarios using cement and sand. Additionally, substituting 10% marble powder for sand led to a 14% enhancement in concrete's compressive strength, while the strength of the mix with a low ratio of water to cement increased by 22%.

In the study of Majeed (2021), with replacement ratios of 0%, 5%, 10%, 15%, and 20%, various mixes of concrete were created. Apart from non-destructive exams such as the velocity of ultrasonic pulses and rebound hammer tests, samples were subjected to destructive tests for their flexural, tensile, and compressive strengths. It was found that adding more cement could increase the strength of the concrete by up to 10%. The compressive strength results were validated by Schmidt rebound numbers.

Within research by Binici *et al*. (2008), 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 from 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*. (2011), 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*. (2012), as a reference, crushed rock was employed, and marble waste was substituted in various proportions for conventional coarse aggregates, including 0%, 10%, 20%, and 40%. According to the findings, the concrete mixes' unit weight decreased by 40%. André (2012) used coarse marble aggregates instead of natural aggregates in another study. Over 28 days, he saw a gain in compressive strength up to 50% substitute. In contrast to the control concrete, compressive strength dropped after 50%. Using leftover marble as coarse aggregates, André (2014) 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 created 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*. (2013), 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*. (2014), coarse aggregates made from residual marble were used to partially replace conventional coarse aggregates in concrete to improve its mechanical properties. Additionally, they 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.* (2016), 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 *et al*. (2020) looked at the feasibility of replacing some coarse aggregate with marble coarse aggregate. They investigated replacement indices ranging from 0% to 100%. As the marble content was increased up to 50%, they found that the flexural, tensile, and compressive strengths had all increased. In their research, Sahu *et al*. (2021), 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. (2022) replaced natural coarse aggregates (NCA) with recycled marble coarse aggregates (RMCA) in percentages of 50% and 100%. The best workability is obtained when natural coarse aggregates are completely substituted with marble coarse aggregates. Black marble waste aggregates were used in place of natural coarse aggregates by Sowjanya *et al.* (2023) in the following proportions: 0%, 20%, 40%, 60%, 80%, and 100%. According to the study's findings, the 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 marble coarse aggregates.

In this study, three series of mixes were prepared. The first series (S1) is composed of 100% natural coarse aggregates. In the second series (S2), 50% of the natural coarse aggregates are replaced with marble coarse aggregates, while the third series (S3) is composed of 100% marble coarse aggregates. In each of the three series, the cement was replaced with marble powder at a percentage ranging from 5% to 20%, increasing by 2.5%. Concrete samples produced with these modifications are evaluated for workability; Schmidt rebound hammer index, 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 the feasibility and environmental benefits of this alternative approach.

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 [24]. 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 [25]. 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, cube-shaped construction 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 size was 4.75 mm. The NF EN 12620 [17] 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 a 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 [23] standard. As an auxiliary material in the process of shaping and cutting, marble companies provided marble dust in the form of powder and Coarse Aggregate. Marble waste was crushed into the crusher to obtain a size ranging from 5 to 20 mm. The Waste Marble Powder (WMP) has a Fineness Blaine of 3320 m^2/kg and a specific gravity of 2.71. The Marble Coarse Aggregate (MCA) 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 particle analyses of the different materials utilized.

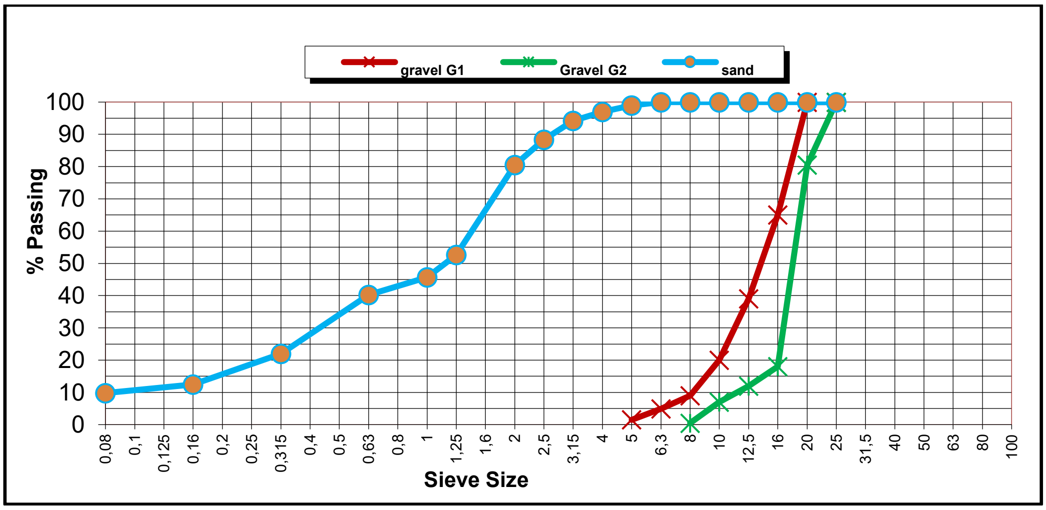


Figure-1. Distribution of sand, gravel G1, and gravel G2 particle sizes.

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 concretes should increase their cohesiveness. The physical characteristics of Cement, WMP, sand coarse aggregate G1, G2, and MCA are presented in Table-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 Table-2. The marble powder X-ray diffraction (XRD) spectrum is seen in Figure-2.

Table-1. Physical characteristics of Cement, WMP, sand, coarse aggregate G1, G2, and MCA.

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.

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

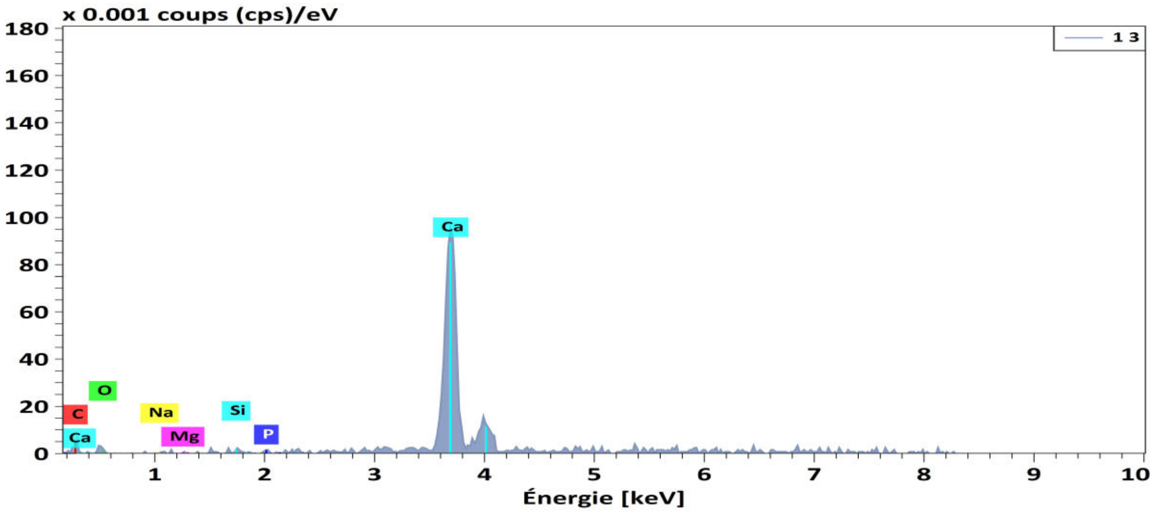


Figure-2. X-ray diffraction spectrum of marble powder.

Table-3. Mixture proportions with w/c=0, 55.

Mix identification	MP (%)	MCA (%)	Water (kg/m^3)	Cement (Kg/m^3)	FA (Kg/m^3)	G1 (kg/m^3)	G2 (kg/m^3)	MP (kg/m^3)	MCA (kg/m^3)
C0-MD-0	0	0	192	350	747	320	815	0	0
C0-MD-5	5	0	192	332,5	747	320	815	17,5	0
C0-MD-7,5	7,5	0	192	323,75	747	320	815	26,25	0
C0-MD-10	10	0	192	315	747	320	815	35	0
C0-MD-12,5	12,5	0	192	305,25	747	320	815	44,75	0
C0-MD-15	15	0	192	097,5	747	240	815	52,5	0
C0-MD-17,5	17,5	0	192	288,75	747	320	815	61,25	0
C0-MD-20	20	0	192	280	747	320	815	70	0
C50-MD-0	0	50	192	350	747	160	407,5	0	567,5
C50-MD-5	5	50	192	332,5	747	160	407,5	17,5	567,5
C50-MD-7,5	7,5	50	192	323,75	747	160	407,5	26,25	567;5
C50-MD-10	10	50	192	315	747	160	407,5	35	567,5
C50-MD-12,5	12,5	50	192	305,25	747	160	407,5	44,75	567,5
C50-MD-15	15	50	192	097,5	747	160	407,5	52,5	567,5
C50-MD-17,5	17,5	50	192	288,75	747	160	407,5	61,25	567,5
C50-MD-20	20	50	192	280	747	160	407,5	70	567,5
C100-MD-0	0	100	192	350	747	0	0	0	1135
C100-MD-5	5	100	192	332,5	747	0	0	17,5	1135
C100-MD-7,55	7,5	100	192	323,75	747	0	0	26,25	1135
C100-MD-10	10	100	192	315	747	0	0	35	1135
C100-MD-12,5	12,5	100	192	305,25	747	0	0	44,75	1135
C100-MD-15	15	100	192	097,5	747	0	0	52,5	1135
C100-MD-17,5	17,5	100	192	288,75	747	0	0	61,25	1135
C100-MD-20	20	100	192	280	747	0	0	70	1135

FA = Fine aggregate, G1= Coarse aggregate of type 1, and G2= Coarse aggregate of type 2.
C0, C50, and C100 indicate that the natural coarse aggregates are replaced by 0%, 50%, and 100% with marble coarse aggregates, respectively, as MD-i, indicates that the cement is replaced with marble powder at a rate of i%.

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 [18]. 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 were used at rates of 0%, 50%, and 100% in place of some Natural Coarse Aggregates, and the cement was replaced with marble powder at a percentage ranging from 5% to 20%, increasing by 2.5%.

3.2.2 Compressive strength

Compressive strength is crucial for assessing the structural capacity of concrete in buildings. To find out the concrete’s compressive strength, 150 mm by 150 mm by

150 mm concrete cubes are cast. According to NF EN 12390-3 [19], compressive strength is measured at curing ages of day 7, day 14, and day 28. The samples were cured under 100% relative humidity and a constant ambient temperature of 27 ± 2°C with water.

Figure-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 [21] 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 Figure-4a. 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 Figure-4b illustrates. Concrete cube specimens are subjected to ultrasonic pulse velocity tests after 28 days.

Figure-4 a. Sonic inspection device.

Figure-4 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 Figure-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 [20]. 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.

Figure-5. Schmidt Rebound Hammer

4. RESULTS AND CONVERSATIONAL ANALYSIS

4.1 Marble Powder's Impact on the Concrete's Workability

In our study, three series of mixes were prepared. The first series (S1) is composed of 100% natural coarse aggregates. In the second series (S2), 50% of the natural coarse aggregates are replaced with marble coarse aggregates, while the third series (S3) is composed of 100% marble aggregates. In each of the three series, the cement was replaced with marble powder at a percentage ranging from 5% to 20%, increasing by 2.5%. The workability of concrete blends was assessed. Table-4, displays the replacement levels of mixtures and their corresponding slump values, which varied between 39 and 66 mm. It was observed that, in the three series, when marble powder is used in place of cement, the slump decreases, even though the incorporation of marble coarse aggregates tends to increase this workability, as illustrated in Figure-6. The increased specific surface area of marble compared to CPJ cement increases internal friction, and the higher water absorption property demonstrated by the marble powder (MP) can be attributed to this. The results show that incorporating marble coarse aggregates at 50% and 100% with the substitution of cement by marble powder up to 7.5% makes the mixes more workable than the control 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. The same observations were made by Hebhoub (2011), Aliabdo (2014), Ashish (2018), and Vardhan (2019).

Table-4. Slumps values.

Percentage of cement replacement by marble powder	0% of marble coarse aggregate incorporation	50% of marble coarse aggregate incorporation	100% of marble coarse aggregate incorporation
0	57	62	66
5	54	59	63
7,5	53	57	61
10	50	52	58
12,5	46	50	54
15	44	48	50
17,5	41	45	48
20	39	43	45

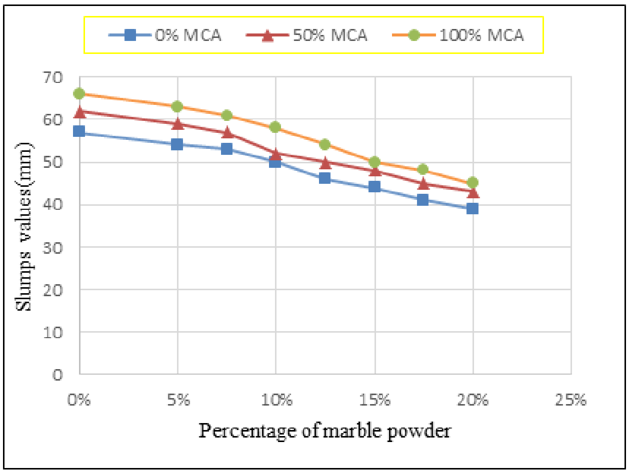


Figure-6. Workability of concrete mixtures.

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 on 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 (UTM), compressive strength results were acquired. The specimens' compressive strengths are displayed in Table-5, where the cement was replaced with marble powder at a percentage ranging from 5% to 20%, increasing by 2.5%, while natural coarse aggregates were replaced with marble coarse aggregates at 0% (S1), 50% in (S2) and 100% in (S3). Where (S1), (S2), and (S3) are the series of mixes mentioned above. It is observed that in the three series of mixes, and at all ages, the compressive strength increases compared to the control mix up to 12.5% cement replacement by marble powder, with a peak reaching 10% replacement. It should also be noted in Figure-7, Figure-8, and Figure-9, that at the age of 28 days, the compressive strength shows an increase of 28.66% and 31.63% compared to the control mix for 50% and 100% replacement of natural coarse aggregates with marble coarse aggregates, respectively.

Given that the C100-MD-10 sample yielded the greatest level of compressive strength, substituting 10% of cement with marble powder and 100% of natural coarse aggregates with marble coarse aggregates represents a practical and effective partial solution for replacing natural cementitious materials with marble by-products.

Table-5. Compressive strength.

Mix designation	Concrete's compressive Strength		
	Day 7	**Day 14**	**Day 28**
C0-MD-0	17,60	21,32	27,94
C0-MD-5	18,92	22,70	30,83
C0-MD-7,5	19,86	23,83	32,37
C0-MD-10	21,96	26,57	33,88
C0-MD-12,5	20,69	23,70	30,65
C0-MD-15	17,25	19,47	25,04
C0-MD-17,5	16,56	18,72	24,28
C0-MD-20	15,52	17,18	22,53
C50-MD-0	19,16	23,56	31,10
C50-MD-5	21,05	25,47	32,63
C50-MD-7,5	22,02	26,42	35,32
C50-MD-10	24,13	28,10	35,95
C50-MD-12,5	22,94	26,28	32,53
C50-MD-15	19,27	22,40	28,23
C50-MD-17,5	18,48	21,76	28,17
C50-MD-20	17,38	20,05	26,23
C100-MD-0	20,97	25,16	31,15
C100-MD-5	22,54	27,04	35,36
C100-MD-7,5	23,44	28,12	36,88
C100-MD-10	25,76	28,96	37,96
C100-MD-12,5	24,24	27,52	35,68
C100-MD-15	23,27	26,52	35,46
C100-MD-17,5	21,87	25,15	33,96
C100-MD-20	20,55	23,22 30,58	

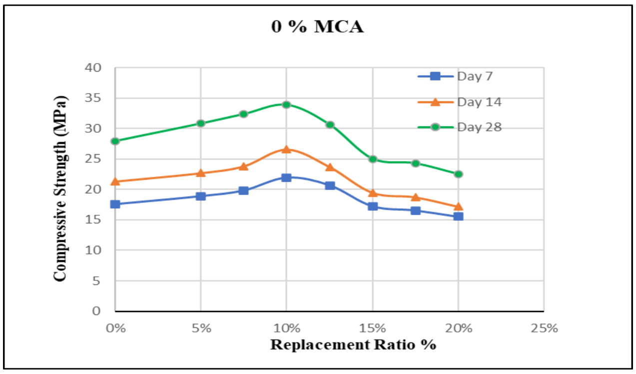


Figure-7. Compressive strength variation with 0% MCA replacement.

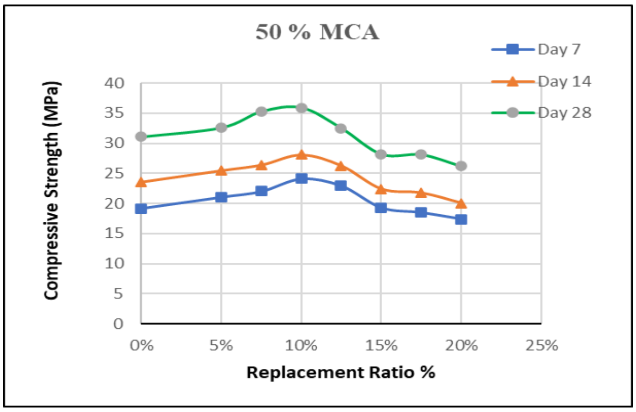


Figure-8. Compressive strength variation with 50% MCA replacement

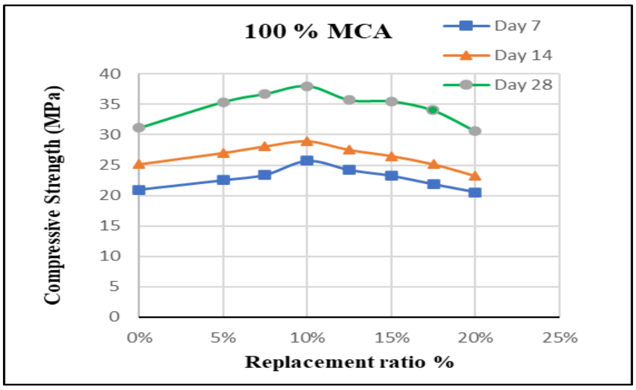


Figure-9. Compressive strength variation with 100% MCA replacement

4.3 Marble Powder's Impact on the Velocity of Ultrasonic Pulses

UPV tests on concrete cube samples are performed at 28 days. Table-6, and Figure-10, present the UPV results of the cement paste. It is crucial to remember that, apart from the C0-MD-20 mixture, 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 18.20%, 27.44%, and 27.98% for concrete mixtures C0-MD-10, C50-MD-10, and C100-MD-100, respectively, compared to the values of the control mixture C0-MD-0. Additionally, the maximum quality of concrete was achieved with 10% utilization of marble powder and 100% 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-6. Compressive strength and UVP at 28 days.

Mix designation	UPV (Km/s)	Compressive Strength
C0-MD-0	3,68	27,94
C0-MD-5	4,07	30,83
C0-MD-7,5	4,25	32,37
C0-MD-10	4,35	33,88
C0-MD-12,5	3,97	30,65
C0-MD-15	3,65	25,04
C0-MD-17,5	3,25	24,28
C0-MD-20	2,97	22,53
C50-MD-0	4,06	31,10
C50-MD-5	4,47	32,63
C50-MD-7,5	4,59	35,32
C50-MD-10	4,69	35,95
C50-MD-12,5	4,26	32,53
C50-MD-15	3,84	28,23
C50-MD-17,5	3,72	28,17
C50-MD-20	3,47	26,23
C100-MD-0	4,10	31,15
C100-MD-5	4,49	35,36
C100-MD-7,5	4,69	36,18
C100-MD-10	4,71	37,96
C100-MD-12,5	4,67	35,68
C100-MD-15	4,53	35,46
C100-MD-17,5	4,25	33,96
C100-MD-20	3,92	30,58

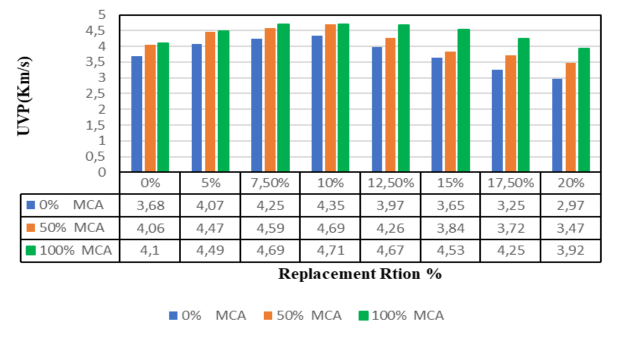


Figure-10. Ultrasonic pulse velocity variation with replacement proportion.

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 Figure-11, Figure-12, and Figure-13. 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 Ultrasonic Pulse Velocity test results. In this case, equations for calculating compressive strength based on the obtained results were established as shown in Figures 11, 12, and 13.

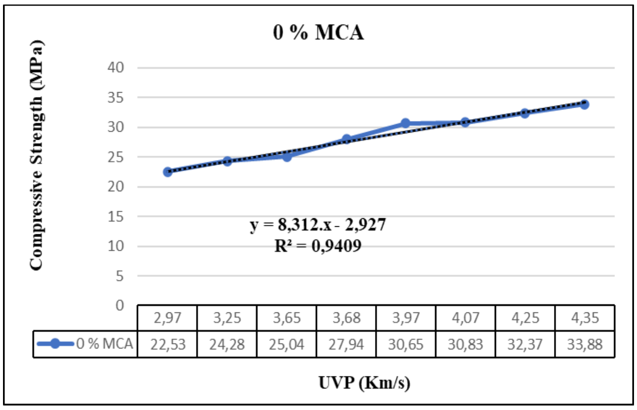


Figure-11. Relationship between ultrasonic pulse velocity and compressive strength for 0% MCA replacement.

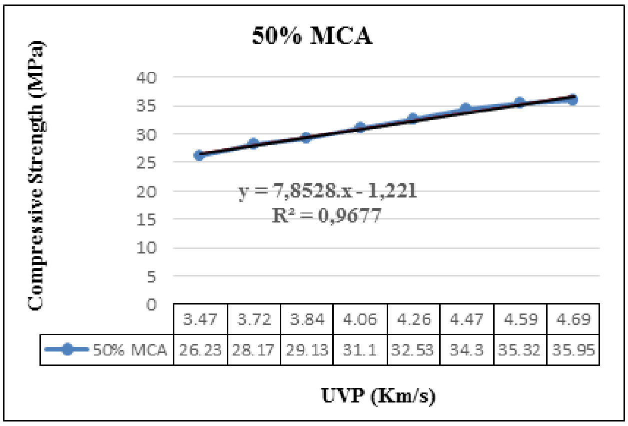


Figure-12. Relationship between ultrasonic pulse velocity and compressive strength for 50% MCA replacement

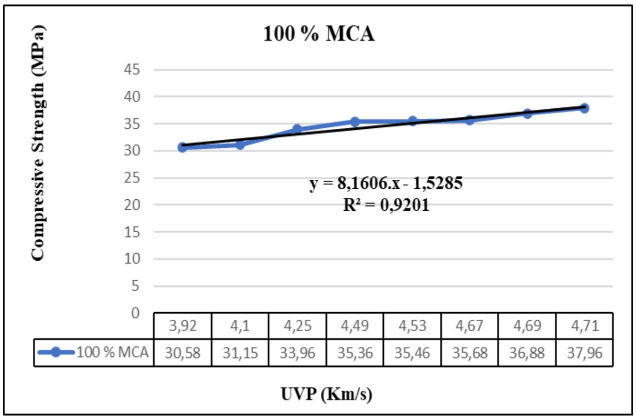


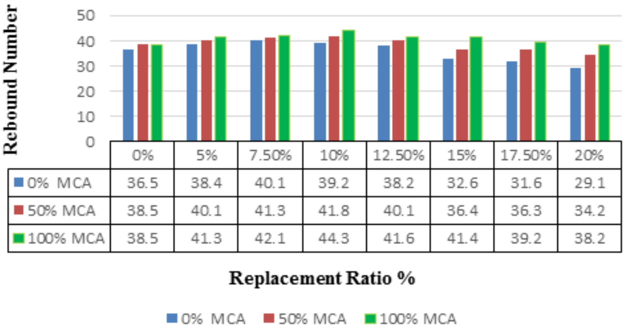
Figure-13. Relationship between ultrasonic pulse velocity and compressive strength for 100% MCA replacement.

4.4 Marble Powder's Impact on the Schmidt Rebound Hammer

Schmidt Hammer tests on concrete cube specimens are conducted at 28 days. Table-7, and Figure-14, present the Rebound Number results of the cement paste. The Schmidt Rebound Number increased by 10.13%, 14.52%, and 21.37% for concrete mixtures C0-MD-10, C50-MD-10, and C100-MD-100, respectively, compared to the values of the control mixture C0-MD-0. Additionally, the maximum Rebound Number was 44.3, achieved with 10% utilization of marble powder and 100% utilization of marble coarse aggregates. In conclusion, the Rebound Number significantly increases when cement is substituted with marble powder and when coarse natural aggregates are substituted with marble coarse aggregates.

Table-7. Compressive strength and rebound number at 28 days.

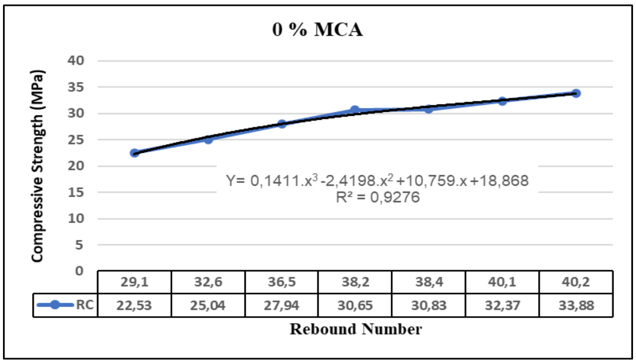
Mix designation	Rebound Number	Compressive Strength
C0-MD-0	36,5	27,94
C0-MD-5	38,4	30,83
C0-MD-7,5	40,1	32,37
C0-MD-10	40,2	33,88
C0-MD-12,5	38,2	30,65
C0-MD-15	32,6	25,04
C0-MD-17,5	31,6	24,28
C0-MD-20	29,1	22,53
C50-MD-0	38,5	31,10
C50-MD-5	40,1	32,63
C50-MD-7,5	41,3	35,32
C50-MD-10	41,8	35,95
C50-MD-12,5	40,1	32,53
C50-MD-15	36,4	28,23
C50-MD-17,5	36,3	28,17
C50-MD-20	34,2	26,23
C100-MD-0	38,5	31,15
C100-MD-5	41,3	35,36
C100-MD-7,5	42,1	36,18
C100-MD-10	44,3	37,96
C100-MD-12,5	41,6	35,68
C100-MD-15	41,4	35,46
C100-MD-17,5	40,2	33,96
C100-MD-20	38,2	30,58



	0%	5%	7.50%	10%	12.50%	15%	17.50%	20%
🟦 0% MCA	36.5	38.4	40.1	39.2	38.2	32.6	31.6	29.1
🟥 50% MCA	38.5	40.1	41.3	41.8	40.1	36.4	36.3	34.2
🟩 100% MCA	38.5	41.3	42.1	44.3	41.6	41.4	39.2	38.2

Figure-14. Rebound number variation with replacement proportion.

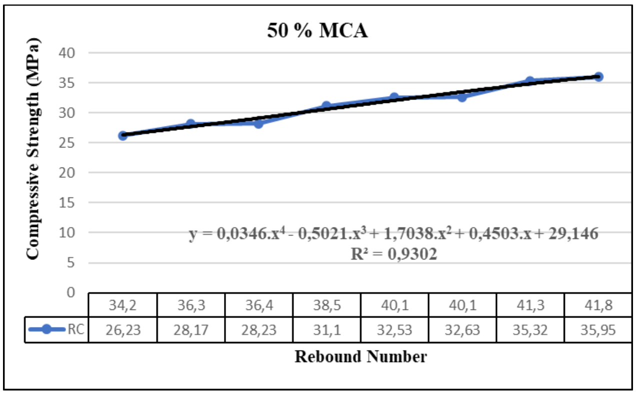
To assess the Rebound Number and Compressive strength of concrete incorporating marble powder and marble coarse aggregate, experimental findings were compared with empirical data, as depicted in Figure-15, Figure-16, and Figure-17. To obtain data close to reality, an analysis of regression applying the method of least squares, a mathematical concept, was conducted to examine the relationships between rebound numbers and compressive strength test results. In this case, equations for calculating compressive strength based on the obtained results were established as shown in Figures 15, 16, and 17.



$Y= 0,1411.x^3 -2,4198.x^2 +10,759.x +18,868$
$R^2 = 0,9276$

	29,1	32,6	36,5	38,2	38,4	40,1	40,2
RC	22,53	25,04	27,94	30,65	30,83	32,37	33,88

Figure-15. Rebound number and compressive strength and relationship for 0% MCA



$y = 0,0346.x^4 - 0,5021.x^3 + 1,7038.x^2 + 0,4503.x + 29,146$
$R^2 = 0,9302$

	34,2	36,3	36,4	38,5	40,1	40,1	41,3	41,8
RC	26,23	28,17	28,23	31,1	32,53	32,63	35,32	35,95

Figure-16. Rebound number and compressive strength and relationship for 50% MCA.

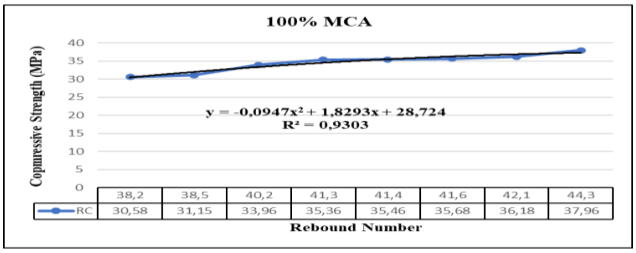


Figure-17. Rebound number and compressive strength and relationship for 100% MCA.

5. CONCLUSIONS

The building industry is continuously growing, and this is depleting natural resources because natural aggregates and cement are becoming more and more necessary. Our main idea was to replace some of the natural coarse aggregates with marble coarse aggregates and some of the cement with marble powder. What worried us was science, not economics. Many tests were conducted to confirm the effects of incorporating leftover marble into concrete. As per the test results, it was found that:

a) The results show that incorporating marble coarse aggregates at 50% and 100%, with the substitution of cement by marble powder up to 7.5%, makes the mixes more workable than the control concrete. Beyond the 12.5% substitution of cement with marble powder, workability decreases despite the incorporation of marble coarse aggregates.

b) The compressive strength shows an increase of 28.66% and 31.63% compared to the control mix for 50% and 100% replacement of natural coarse aggregates with marble coarse aggregates, respectively

c) The quality of concrete is not affected when marble powder is used as a replacement for cement and when marble coarse aggregates are used instead of natural coarse aggregates. The velocity of ultrasonic pulses increased by 18.20%, 27.44%, and 27.98% for concrete mixtures containing 10% marble powder replacing cement and 0%, 50%, and 100% marble coarse aggregates, respectively, compared to the values of the control mixture.

d) -Based on the test results, it is clear that there is a good approximation of the compression strength obtained from the universal testing machine and the compression strength determined using the Schmidt hammer conversion chart.

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