Research on Engineering Structures & Materials

www.jresm.org

Research Article

Statistical modeling and optimization of recycled concrete properties enhanced with marble fines using response surface methodology

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Article Info

Article History:

Received 08 Mar 2025

Accepted 05 June 2025

Keywords:

Recycled aggregates concrete;
Marble powder fines;
Physical-mechanical characteristics;
Statistical relationships;
Central composite design

Abstract

The reuse of demolished concrete waste is a promising approach for conserving natural resources and protecting the environment. This study investigates the impact of incorporating 0%, 5%, 10%, 15%, and 20% marble fines into recycled aggregate concrete (RAC) using Central Composite Design (CCD) based on the response surface methodology (RSM). The study evaluates multiple physical and mechanical properties to identify the optimal marble fine content. Results show that recycled concrete with 20% marble fines (RC20) exhibits exceptional quality in terms of fineness modulus, enhancing fresh density and reducing slump in the fresh state. Additionally, 10% and 15% marble fines significantly enhance the mechanical properties of hardened RAC. Specifically, RC10 (10% marble fines) increases compressive strength by 13.79% and reduces capillary absorption by 46.75% compared to the control (RC0) after 60 days. The inclusion of 15% marble fines notably improves flexural strength at the same hydration period compared to other formulations. Polynomial correlations, with an R-squared value ≥ 0.98, were established to relate fresh concrete properties (density, slump) and hardened concrete characteristics (porosity, water absorption by immersion) following marble fine addition. The RSM-based CCD model validates an effective approach, yielding optimal compressive strength (35.9 MPa) and flexural strength (4.92 MPa) with a desirability coefficient of approximately 93%, demonstrating the potential of marble fines in enhancing RAC performance.

1. Introduction

The protection of the environment and the conservation of natural resources have become significant socioeconomic concerns. Concrete is the second most widely used building material globally, after water. However, the construction industry faces the challenge of modifying its production and/or application techniques to adopt methods that are in line with sustainable development. In recent years, there has been a considerable increase in the number of constructions in the building sector, which has resulted in an ever-increasing need for raw materials. However, natural deposits of potentially exploitable aggregates are becoming more and

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DOI: http://dx.doi.org/10.17515/resm2025-731ma0308rs

more scarce. Thus, industrialists are facing increasing difficulties in supplying aggregates. Recycling allows for better resource management by recovering wastes and saving traditional natural aggregates. Its environmental and ecological impact is also conditioned by the limitation of deposition areas, the opening of quarries, and the exploitation of alluvial beds [1]. Recycling is further supported by regulations for the creation of new quarries, which are linked to futuristic visions for developing the recycling sector. Numerous experimental studies have demonstrated the feasibility of using cementitious materials based on recycled aggregates, with encouraging results.

Partial or total replacement of traditional aggregates with demolition aggregates leads to concretes with results inferior to ordinary concretes [1]. However, several studies indicate that the use of fines particles from concrete demolition in mortar production improves mechanical properties, and also demonstrates its practical effectiveness in mixing up to 15% fines into mortar formulation [2,3]. These studies also validate the substitution of fine aggregate fractions with a granulometry > 0.6 mm by those of demolition concrete in mortars [2,4]. Other research indicated that the presence of 20% of concrete demolition aggregates, as well as 15% mixed recycled aggregates extracted through demolition and construction waste in mortar showed a better performance [2,5,6]. The inclusion of recycled aggregates in concrete mixes results in a reduction in its mechanical properties versus ordinary concrete [7–10]. In their studies, Kachouh et al. [7,11] examined the impact of full incorporation of recycled concrete aggregates (RCA) on the compressive strength of concrete. Their results indicate that when RCA completely replaces the aggregates, the compressive strength reduces by about 24% compared to that obtained with natural aggregates. Kachouh et al. [7] and Corinaldesi [12] studied the effect of substituting natural fine aggregate with RCA fine aggregate on the mechanical behaviour of concrete. They found that a maximum replacement of 30% achieved the target compressive strength. However, when this replacement was carried out with RCA, the modulus of elasticity showed a reduction of 15% compared with concrete containing natural aggregates. Kachouh et al. [7] and Malešev et al. [13] examined the properties of fresh and hardened concrete using different percentages of RCA replacement (0%, 50% and 100%). The authors concluded that fresh concrete bulk density, wear resistance and elastic modulus decreased as the amount of RCA increased. Interestingly, when RCA obtained by grinding high-strength concrete was used, the compressive strength was not affected compared to concrete using natural aggregates. However, the characteristics of concrete made from RCA were influenced by the source of the RCA used [7,13,14]. Concrete produced with RCA from an unknown source had less compressive and tensile strength than concrete manufactured with RCA from a known source.

Today, the regression method RSM has been observed in the field of cementitious materials in civil engineering to predict and/or optimize their characteristics in the fresh and hardened states [15–20]. However, these methods have been little used in the field of materials recycling, especially recycled concrete, with only a few studies exploiting them [21,22]. The RSM method is a machine learning approach for predicting the impact of independent variables on results. This approach requires the use of a non-linear regression model to determine optimal conditions [23], while minimizing the number of experiments required [24].

This study aims to enhance the properties of concrete composed entirely of recycled materials by incorporating recycled concrete aggregates (RCA) mixed with varying proportions of recycled marble fines (0%, 5%, 10%, 15%, and 20%) as a substitute for recycled fine sand derived from demolished concrete. The impact of this substitution was investigated across multiple parameters, including slump, fresh density, compressive strength, flexural strength, porosity, absorption by immersion, capillary absorption, and the softening coefficient. Furthermore, polynomial regression models, derived from analysis of variance (ANOVA), were developed to correlate the physical performance of fresh and hardened concrete states and to predict the physical characteristics of recycled aggregate concrete (RAC) containing marble fines that have not already been performed. Response Surface Methodology (RSM) optimization was employed to estimate input parameters (percentage of marble fines and hydration duration) and output parameters (compressive and flexural strength).

2. Experimental Procedure

The diagram below illustrates the key stages in an experimental study to assess the properties of ecological concrete incorporating recycled aggregates and marble fines. It details the logical progression from material preparation to analysis using RSM methodology. Each step is represented to clarify the process of research and optimization of mechanical performance. (Fig. 1) presents the flowchart summarizing the production schedule and testing timeline for the different concrete studied.

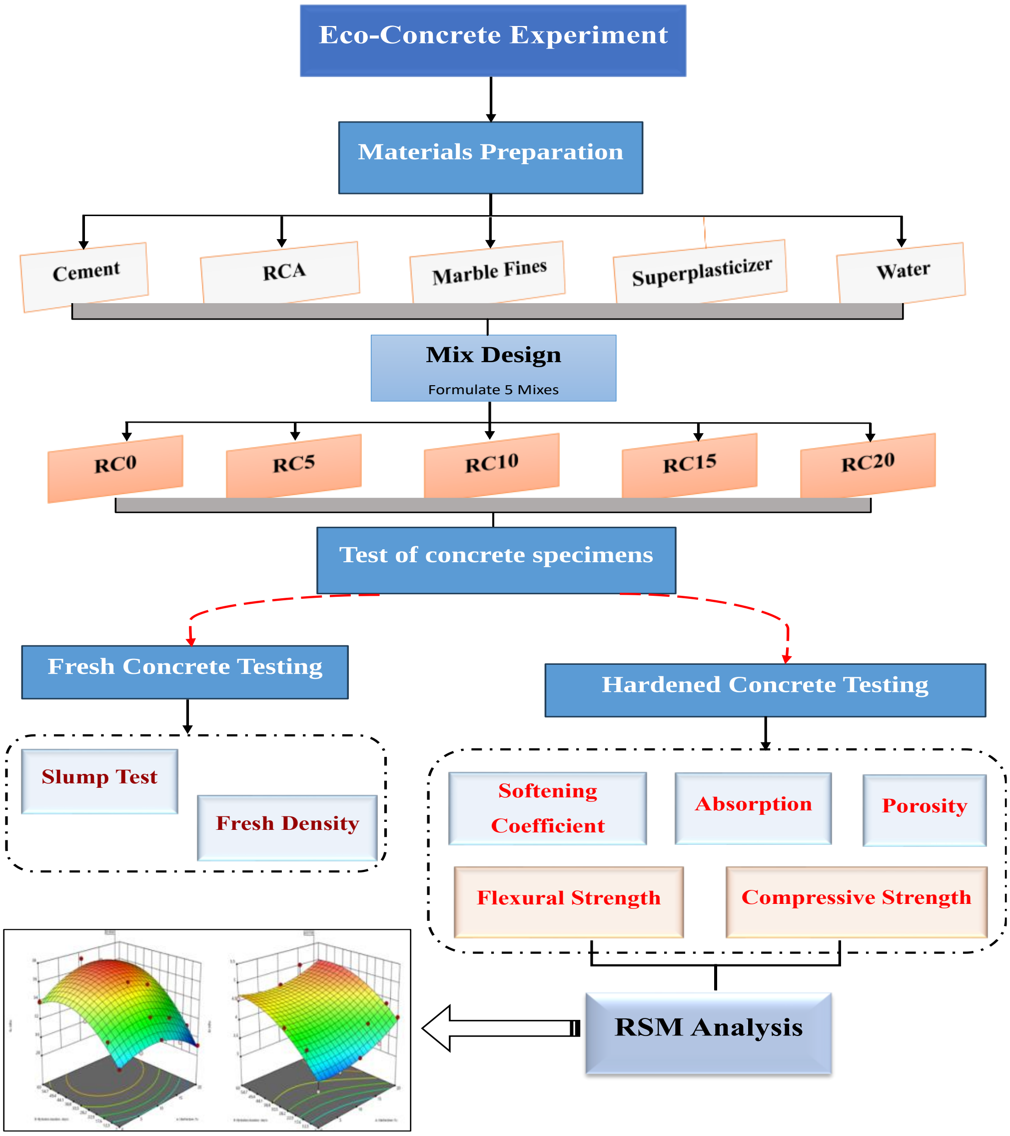


Fig. 1. Flowchart illustrating the research process

2.1. Cement

The type of cement used in this investigation is: CEM II/B-L 42.5N limestone Portland cement manufactured at the SPA BISKRIA CEMENT factory. Table 1 shows the chemical, mineralogical and physical-mechanical properties of this cement.

2.2. Adjuvant (Super Plasticizer)

The admixture used in this study is a light-brown, liquid superplasticizer with high water-reducing properties, enabling the production of high-quality concrete and mortar.

This admixture, marketed under the name MEDAFLOW 145 by GRANITEX, has a density of 1.065 ± 0.015. Its pH is between 5 and 6, its chloride content is less than 1g/L, and its dry extract is 30 ± 1.5%, in compliance with NF EN 934-2 [25] and NA 774 [26] standards. The manufacturer authorizes a percentage of use ranging from 0.3% to 2.0% of cement weight, i.e., 0.33 to 1.8 liters per 100 kg of cement.

Table 1. Technological properties of cement powder

Chemical composition [% wt]				Bogue composition (%)	
SO_3	Cl^-	MgO	Loss on ignition	C_3S	C_3A
2.4 - 2.8	<0.05	< 3.5	7.5 - 9.5	58 - 66	5.1-7.2

Physical and mechanical properties	
Start of setting [min]	150-200
End of setting [min]	220-290
Cement paste consistency [%]	26.5- 28.4
Hot expansion [mm]	0.0 - 1.0
28-day compressive strength in [MPa]	42.5- 52.5
2-day compressive strength in [MPa]	15-25

2.3. Mixing Water

The water for manufacturing concrete mixes is tap water, which in principle is free from impurities. Its temperature is not controlled during mixing, although the concrete obtained has a temperature of around 20 ± 2°C. However, it complies with the specifications of standard NF P 18-303 [27].

2.4. Aggregates

The aggregates used were extracted from recycled demolished concrete and divided into three classes: sand 0/5 RS, gravel 5/10 and 10/16 RG as shown in Fig 2. The preparation and obtaining of granular classes are done by crushing, screening and sieving.

The granulometric distribution of demolition concrete aggregates with and without marble fines is presented in Fig 3. The chemical and physical-mechanical characteristics of the used aggregates are presented in Table 2 and Table 3 respectively. The fineness modulus values for demolished sand are 3.11, and sand samples graded RS 5%mf, RS 10%mf, RS 15%mf and RS 20%mf are: 2.96, 2.81, 2.65 and 2.50, respectively.

2.5. Marble Fines

The marble fines (m_f) used in this study, come from the marble factory of Chaabani, Bayadha [Algeria] in the form of granules and small pieces, which are ground manually. These properties are presented in Table 2 and Table 3 sequentially.

Table 2. Investigation of various aggregates using XRF spectroscopy

Materials	Chemical composition								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
Marble Powder	0,88	0,37	0,13	51,69	0,94	0,07	0,02	0,09	42,98
Demolished Concrete	21,29	6,13	2,27	52,86	1,75	1,79	0,58	0,98	10,33

LOI: Loss on Ignition

2.6. Experimental detail

According to EN 12350-2 [28], the slump test consists of filling concrete into a truncated sheet metal mold. The concrete was placed in three layers packed with a steel rod of 16mm diameter with a rounded end, at a rate of 25 strokes per layer. The mold was then carefully lifted and the slump was measured. The density of fresh concrete was measured using a watertight and sufficiently rigid container as specified in EN 12350-6 [29]. The concrete was put into the container and vibrated with a vibrating table, after appropriate levelling. The container and its contents must be weighed to determine the density, which can be obtained using the following Eq (1):

$$D = \frac{(M_2 - M_1)}{V} \tag{1}$$

Where, D - density of fresh concrete, expressed in [g/cm^3]; M_1 - mass of container in grams; M_2 - total mass of container, including concrete, in grams; V - container volume in cubic centimeters.

The compressive strength of the concrete tested was measured by evaluating the applied load leading to crushing by axial compression, in accordance with EN 12390-3 [30], using three 10x10x10 cm cubic specimens per formulation (Fig. 4). The bending test involves breaking a prismatic sample of dimensions 7 x 7 x 28 cm by subjecting it to a flexural moment (Fig. 4), while applying a load according to the advice of the standard NF EN 12390-5 [31]. During the test, the maximum load recorded is noted, and the bending strength is determined by performing the appropriate calculation. A capillary water absorption test was carried out in accordance with ASTM C 642 [32]. As a first step, to get complete drying, samples measuring 7 x 7 x 7 cm were placed in an oven at 70°C until they reached a constant mass such that Δm /day 0.1%. In the next step, all the external faces of the sample were waterproofed with paraffin, except for the face that is in direct contact with water. Then the dry mass was measured and this face was also placed in a basin of water 5 mm thick. The mass of each specimen was subsequently determined at the following times [10, 20, 30, 40, 50, 60, 70, 80, 90] min, 24 h, 48 h and 72 h. Then, for each measurement time t, the capillary absorption coefficient could be defined by the following Eq (2):

$$C_t = \frac{(M_t - M_0)}{A} \tag{2}$$

Where, Ct – absorption coefficient at time t [g/cm^2]; A – sample cross-sectional area [cm^2]; M_t – Mass at time t [g]; M_0 – initial sample mass [g].

Fig. 2. a) Demolished concrete, b) RG 10/16, c) RS 0/5 and d) RG 5/10

The water-accessible porosity test was conducted in accordance with ASTM C 642 [32]. Experimentation proceeds as follows: drying of the sample 10 × 10 × 10 cm in the oven at 70 °C during 24 hours, until a steady mass is reached, in order to evaporate all the water, this mass is noted M_{dry}. The sample was also immersed in water during a period which lasted 24 hours, after removal from the water, the sample was left in the open air for 5 hours, then subjected to weighing. M_{air}, another weighing process of the sample in water was also carried out (hydrostatic weighing) M_{water}. The porosity accessible to water is defined by Eq (3):

$$V_p = \frac{(M_{air} - M_{dry})}{(M_{air} - M_{water})} \ x \ 100 \tag{3}$$

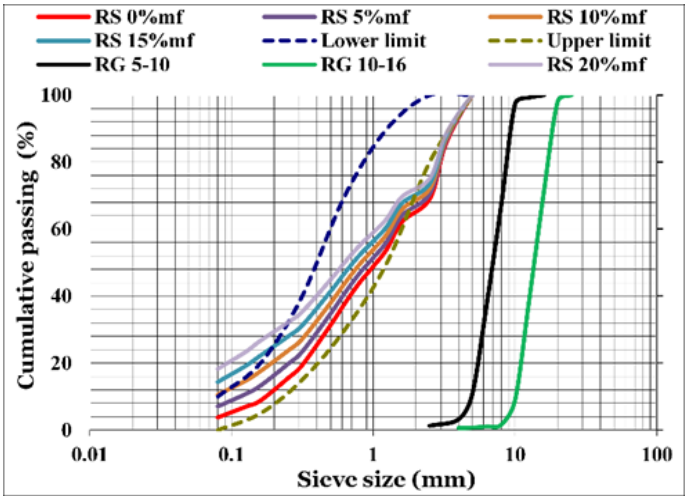


Fig. 3. Particle size analysis of studied aggregates

The test of absorption by immersion is carried out according to a simple method. The specimens of concrete 10 x 10 x 10 cm studied of 60 days of age are weighed after their passage in the oven at 70°C, from where they are withdrawn only after stabilization of their weight [i.e., M_{dry}]. Then they are completely immersed in water 20°C ± 5°C until saturation of the material, then withdrawn and weighed, [i.e., M_{sat}]. The water absorption capacity is expressed as follows Eq (4):

$$A\ \% = \frac{(M_{sat} - M_{dry})}{M_{dry}} \ x100 \tag{4}$$

The immersion absorption value is taken as the average of three specimens of each composition. The softening coefficient is defined as the ratio between the compressive strength of a water-saturated material (R_{sat}) and the compressive strength of the same material in a dry state (R_{dry}). The strengths R_{sat} and the R_{dry} are measured on 10 × 10 × 10 cm cubic specimens at 60 days of age. It is defined by the following Eq (5):

$$k_{sof} = \frac{R_{sat}}{R_{dry}} \tag{5}$$

Where, K_{sof} - softening coefficient; R_{sat} and R_{dry} [in MPa]

Fig. 4. Photographs of the cubic and prismatic samples

Table 3. Technical characteristics of the aggregates used and previous study results

Physical-mechanical characteristics	Results obtained				Results of previous studies			
	RS 0/5	RG		*mf*	RS	RG		
d/D	0/5	,5/10	10/16		0/5	6/20	5/12.5	12.5/20
Absolute density g/cm³	2.38	2.50	2.48	2.70	2.56 [33]	2.28 [33]	1.98 [33]	
Apparent density g/cm³	1.35	1.3**0**	2.29		1.04 [33]	1.14 [33]	1.09 [33]	
Fineness modulus MF	3.11				2.40 [34]			
Flattening coefficient %		6.34					10.10 [34]	
Superficial cleanliness		92.18					97.7[34]	99.00[34]
Sand equivalent (visual) %.	87.27				65.40 [34]			
Sand equivalent (plunger)	88.54							
VB: Methylene Blue	0.17				0.17 [34]			
Water content %	2.56	1.50		1.55	3.13 [34]		0.85 [19]	0.90 [34]
Water Absorption Coefficient %		3.76		0.15	7.09 [34]	11 [35]	6.25[34]	5.36 [34]
Void Index %	80.80							
Porosity %	44.45			0.35				
Compactness %	55.55			99.65				
Los Angeles		34.10				26.00 [1]	38.88[34]	36.20 [34]
Micro-Deval		33.65				31.00 [1]	36.50[34]	38.60 [34]

2.7. Concrete Mix Proportions

Concrete mix design was carried out using the Dreux-Gorisse method [36]. The mixes have been designed to achieve a class C25/30 target strength at 28 days of age in accordance with European standard EN 206-1 [37], and they were produced using a W/C ratio of 0.62 and including a 2% superplasticizer. Five different concrete mixes were formulated and kept after demolding in potable water until the day of crushing, to assess the effect of containing marble fines in various RAC formulations [RC0, RC5, RC10, RC15, and RC20] on the physical and mechanical behavior of eco-concrete with marble fines. The aggregates used in this study were not pre-treated. Table 4 provides detailed information on the mixing proportions for the different concretes produced. Ratings used:

- RC0: 100% recycled concrete aggregate, 0% marble fines;
- RC5: Aggregate concrete 95% RS, 100% RG and 5% marble fines;
- RC10: Aggregate concrete 90% RS, 100% RG and 10% marble fines;
- RC15: Aggregate concrete 85% RS, 100% RG and 15% marble fines;
- RC20: Aggregate concrete 80% RS, 100% RG and 20% marble fines.

Table 4. Proportions of the mixture of different concretes in kg/m³

Designation	Proportions [kg/m³]				
	RC0	RC5	RC10	RC15	RC20
Cement	350	350	350	350	350
Marble fines	0.000	37.065	74.130	111.195	148.260
RS 0/5	741.300	704.235	667.170	630.105	593.040
RG 5/10	338.550	338.550	338.550	338.550	338.550
RG 10/16	570.920	570.920	570.920	570.920	570.920
Mixing water	216.660	216.660	216.660	216.660	216.660
Water/cement ratio [W/C]	0.62	0.62	0.62	0.62	0.62
Super plasticizer	7.00	7.00	7.00	7.00	7.00
Theoretical Density [kg/m³]	2224.43	2224.43	2224.43	2224.43	2224.43

2.8. Mathematical Models Using RSM Methodology

Surface Response Methodology (RSM) is an approach that aims to investigate the relationships between independent variables (input variables) and observed results (output responses) using mathematical and statistical techniques [38]. In this study, the Central Composite Design (CCD) was used to analyze data relating to eco-composites composed of eco-concretes containing marble fines as a partial replacement for recycled sand. Design Expert 13 software was used to implement this design, which comprises 2 factors and 2 responses. A series of 20 experiments was carried out to optimize the compressive and flexural strength values. For the design of a CCD with two extreme levels of factors (+1 and -1), the complete factorial design is represented by 2^k, while the axial points are represented by 2k, where C represents the central points. The number of repetitions of each experiment, carried out to reduce experimental error, is denoted by *n*. The total number of repetitions of the experiment can be calculated as follows Eq (6).

$$N = 2^K + 2K + nC \tag{6}$$

The fundamental principle of Response Surface Methodology (RSM) is to develop regression models to assess the correlations between independent variables and output variables, taking into account the different levels of these variables. In this approach, a second-order polynomial is used to model the relationships between the variables Eq (7).

$$Y = \beta_0 + \sum_{1}^{k} \beta_i X_i + \sum_{1}^{k} \beta_{ij} X_i X_j + \sum_{1}^{k} \beta_{ii} X_i^2 + E \tag{7}$$

β_0, β_i, β_{ii}, and β_{ij} are the model coefficients for the intercept, linear, quadratic, and interaction terms, respectively, and X_i, and X_j variables.

Table 5. Coding and levels for CCD model by RSM

Factors	Levels			
	Coded	Min (-1)	Medium (0)	Max (+1)
Marble fines (%)	A	0	10	20
Hydration duration (days)	B	7	28	60

Table 6. Design properties by RSM

		Input factors		Outputs	
Runs	Code	Marble fines (%)	Hydration duration (days)	Compressive strength (MPa)	Flexural strength (MPa)
1	RC_0	0	7	30.200±1.687	2.820±0.103
2	RC_5	5	7	30.133±1.040	3.290±0.102
3	RC_{10}	10	7	33.867±2.623	3.257±0.554
4	RC_{15}	15	7	28.067±2.344	3.456±0.091
5	RC_{20}	20	7	30.250±1.098	4.216±0.026
6	RC_0	0	14	33.650±0.950	4.450±0.230
7	RC_5	5	14	31.283±0.610	3.487±0.425
8	RC_{10}	10	14	33.963±0.491	3.858±0.351
9	RC_{15}	15	14	31.063±2.054	4.039±0.021
10	RC_{20}	20	14	33.143±2.236	4.417±0.051
11	RC_0	0	28	34.550±2.450	4.500±0.180
12	RC_5	5	28	33.867±2.050	3.827±0.301
13	RC_{10}	10	28	39.100±1.283	3.948±0.099
14	RC_{15}	15	28	35.000±2.639	4.133±0.527
15	RC_{20}	20	28	31.200±2.218	4.593±0.640
16	RC_0	0	60	34.067±0.170	4.220±0.397
17	RC_5	5	60	30.333±2.185	4.447±0.340

18	RC_{10}	10	60	38.767±1.517	4.678±0.225
19	RC_{15}	15	60	38.633±2.288	6.019±0.186
20	RC_{20}	20	60	34.500±0.990	4.186±0.261

Table 5 shows the parameters and their specific percentage levels for marble fines (A) and hydration duration (B) used in the experimental design. The different levels of the factors, in the Design of Experiment methodology, are represented by the codes (−1) and (+1), which correspond respectively to the minimum and maximum values centered around a mean value (0). The aim of the Response Surface Methodology (RSM) method is to propose regression models to assess the impact of factors on compressive and flexural strengths values of eco-concrete. To carry out this study, 20 experiments were carried out. Table 6 presents the detailed experimental design, with the different variables used and their respective levels during the tests. It also shows the experimental results for compressive strength and flexural strength.

3. Experimental Results Analysis and Discussion

3.1. Fresh Concrete Properties

Figure 5 illustrates the results showing how the incorporation rate of marble fines affects the workability of Recycled Aggregate Concrete (RAC) made from demolished aggregates. The mixes are prepared using a constant water-to-cement (W/C) ratio and a percentage of superplasticizer equal to 0.62% and 2%, respectively. The increase in slump is strongly influenced by the presence of marble fines and the reduction in the amount of demolition sand. It is crucial to note that the rate of slump increases in proportion to the percentage of marble fines added. At the same time, the reduction in demolition sand content also contributes to this increase. This relationship is explained by the lower absorption capacity of marble fines compared to recycled concrete aggregates [39,40]. When making concrete with recycled aggregates, a certain difficulty in placing them compared to ordinary concrete has been noted. Indeed, this relationship is attributable to the high-water absorption and high porosity of these aggregates.

Figure 5 also illustrates the variation in concrete density as a function of the rate of incorporation of marble fines in combination with recycled concrete aggregates. It is observed that density increases in proportion to the amount of marble fines present. In fact, marble fines have a higher absolute density than recycled sand [39]. The densities of RC5, RC10, RC15, and RC20 are respectively 1.41%, 3.77%, 4.24%, and 5.18% higher than RC0, then the values of fineness modulus of recycled concretes adjusted with marble fines are advantageous than that of RC0 (as seen in Table 3).

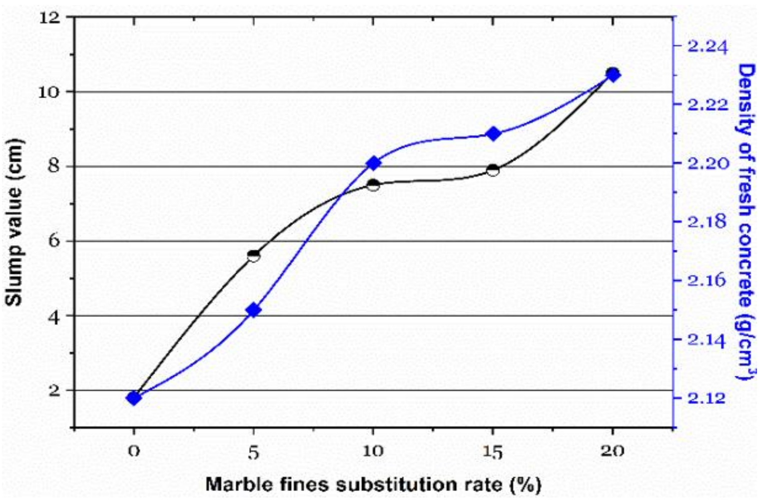


Fig. 5. Effect of marble fines incorporation rate on fresh concrete's workability and density

Finally, the particles of fines fill the voids and improve the density in the fresh state. In this context, it should be noted that RC20 concrete with a fineness modulus of 2.5 has resulted in a decrease in void volume. Indeed, a good arrangement of the solid grains has been achieved, which finally increases the fresh density [41].

3.2. Hardened State Concrete Properties

3.2.1. Compressive Strength

The compressive strength of each mix was evaluated using three 10×10×10 cm cubic samples at 7, 14, 28, and 60 days after concrete preparation Fig. 6a. The evolution of this strength was determined according to the number of fine marbles, as shown in Fig. 7.

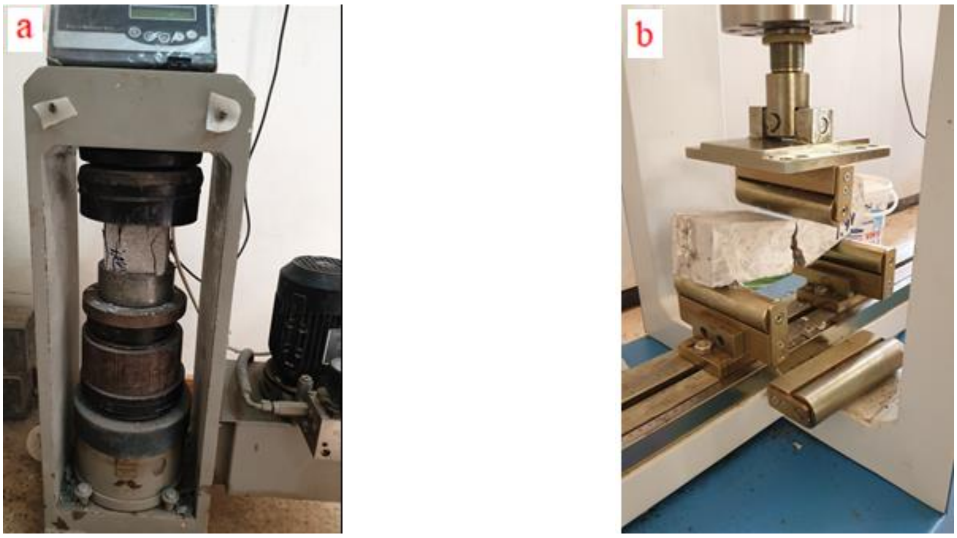


Fig. 6. (a) Compressive strength testing of concrete, (b) Flexural strength testing of concrete

It has been observed that the strength increases gradually over time, reaching its maximum at around 10% and 15% marble fines. The last two percentages increased respectively by 13.17%, 1.30% at 28 days, and 13.79%, 13.38% at 60 days. On the other hand, concrete made with demolition aggregates crushed with 5% and 20% marble fines exhibited lower compressive strength than RC0. This was confirmed by Sadhouari et al [42], who stated that concretes made with crushed sands of different fines content of the order of 0%, 5%, 10%, 15%, and 20% pass through a minimum of 10% to 15% fines with respect to the assessment of occluded air.

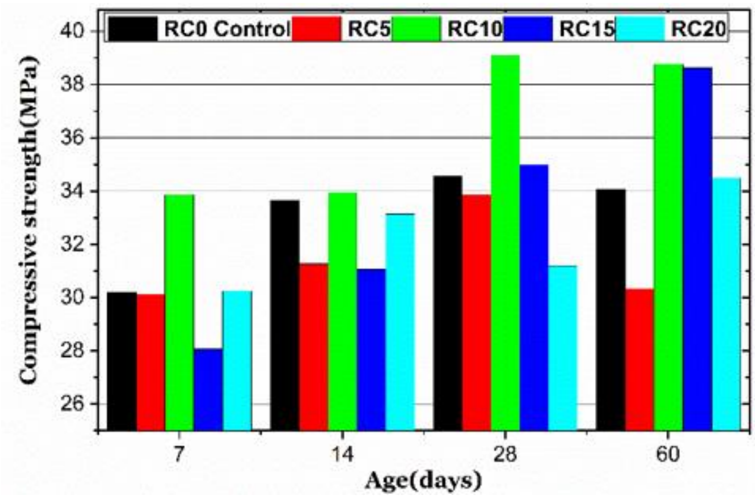


Fig. 7. Compressive strength of different RAC formulations and marble fines

Researchers Berredjem et al [40] found a negative influence of the use of recycled concrete aggregates on the mechanical properties of concrete, such as compressive strength and splitting tensile strength. However, it is important to note that compressive strength is maintained when using class C 25/30. According to Ghorbani et al [43], as the quantity of recycled concrete waste used as a partial substitute for traditional aggregates increases, concrete strength decreases.

Similarly, Kirthika and Singh [44] reported that the optimum rate of river sand substitution by recycled fine aggregate (RFA) was 30%. They observed that at 56 days, concrete made with 30% RFA showed an increase of around 11% in compressive strength, 3.8% in tensile strength, 9.7% in flexural strength, and 4% in modulus of elasticity by comparison with concrete made with river sand. The probable improvement in the mechanical properties of RFA30 is attributable to the high-density structure and lower porosity of RFA-based concrete. In the same way, Benabed et al [45] concluded that when the fines percentage exceeds 15% [in our case RC20 of 18.27%] the strength drops.

3.2.2. Flexural Strength

The Flexural Strength testing was conducted in compliance with NF EN 12390-5 [31]. The average flexural strength of every mixture was evaluated using three prismatic samples measuring 7× 7×28 cm for 7, 14, 28, and 60 days (fig 6b). Fig. 8 shows the variation in flexural strength as a function of marble fines content. The pattern is similar to that observed for compressive strength (Fig.7) Under specified NF EN 206-1 [37], flexural strength values obtained at 60 days for all concrete mixes are significantly higher compared to the flexural strength of RC0 reference concrete for class C 25/30 concretes.

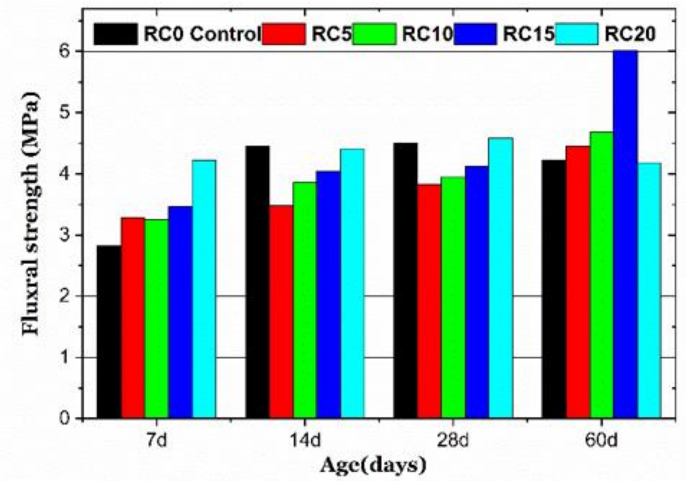


Fig. 8. Flexural strength of different RAC formulations and marble fines

Flexural strength trends are visible up to the final maturity date (60 days), which proves the effectiveness of the existence of marble fines in this type of concrete, except for RC20, which presented a loss of 8.93% at 60 days compared to the 28 days value. It was also found that the values of the maximum breaking force applied in this test are 5.10 KN and 6.55 KN obtained in RC10 and RC15 concrete, respectively, at 60 days. The flexural strength increases during this investigation in all the concretes studied. For the 0% marble fines RC0 concrete, the flexural strength starts with 2.82 MPa at 7 days and reaches the order of 4.50 MPa after 28 days. in RC20 concrete, the flexural strength starts with 4.22 MPa at 7 days and remains almost the same at 28 days. Finally, the optimal substitution rate of marble fines is 10% and 15%. Therefore, we can deduce that the bending strength of concrete made from recycled aggregates and marble fines has been evolving slightly with time. It can be concluded, that the main factors affecting mechanical strength are: cement hydration, fines quality, and relative humidity of the storage environment. This finding was confirmed by Kirthika, and Singh [44].

3.2.3. Capillary Water Absorption Test

Water absorption coefficient is an important predictor of concrete durability. To enable a comparison of the water absorption of samples based on the capillary action of water, it was decided to carry out a capillary water absorption analysis, and to identify the influence of marble fines in the composition based on Recycled Concrete Aggregates (RCA) to the studied mixtures. The kinetics of absorption was studied under normal conditions of laboratory for all types of concretes at 60 days. The results indicated that capillary water absorption was affected by the percentage substitution of marble fines and recycled aggregates of different RAC types, as illustrated in Fig. 9.

In this context, the order of the capillary absorption curves does not necessarily follow the increase in the percentage of marble fines. An optimum level of around 10% effectively clogs the interstitial pores, while limiting the circulation of water inside the specimens due to physical and chemical changes in the concrete matrix [46]. However, above 15%, excessive absorption is observed. This is because the marble fines begin to replace the demolition sand grains, altering the structure of the recycled concrete that the fines were intended to improve [47]. Absorption values showed an increase in all mixtures as time progressed. RC5 and RC10 concrete showed a decrease of 23.38% and 46.75% compared to RC0. This observation is in line with the results reported by Bertrandy and Coquillat [48], who stated that for plastic consistency, the optimum filler content seems to be between 8% and 12% in the crushed sand [in the present study the RC10 fines is about 10.57 %]. Furthermore, Benabed et al [45], concluded that when the percentage of fines exceeds 15% [in this study RC20 of 18.27%] the strength drops. The reason is that the quantity of cement paste is insufficient to envelop all the fine aggregate particles [41]. Other researchers have reported that recycled concrete absorbs more water than concrete containing siliceous aggregates. Olorunsogo et al [49] reported that concrete made from fully recycled aggregates absorbed around 39% more water than concrete made from ordinary aggregates after drying for 28 days.

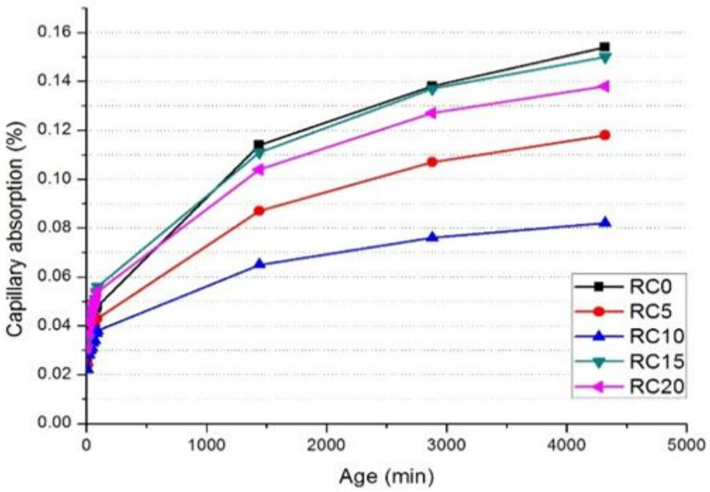


Fig. 9. Capillary water absorption values at 60 days of recycled demolition concrete with and without marble fines as a function of time

3.2.4. Porosity Test and Immersion Water Absorption

Water accessible porosity and water absorption by immersion are two major indicators of the durability of concrete. Indeed, these parameters characterize the ability of the material to let aggressive agents penetrate and circulate, either in liquid or in gas phase. From (Fig. 10) it was found that the porosity of different formulations varied similarly to the absorption by immersion. RC0 has a high porosity compared to RC5, RC10, RC15, and RC20. The RC20 and RC15 concrete samples showed a reduction of 24.47% and 20.88%, successively, compared to the RC0 at 60 days. With regard to water absorption by immersion, the RC20, RC15, and RC10 concretes had percentages of 21.24%, 18.93%, and 16.33%, respectively, which are lower than the RC0 at the last deadline. RC20 concrete has obtained the minimum percentage of porosity and absorption by immersion compared to RC10 and RC15. Its compressive strength is decreased compared to RC10 and RC15 due to the reduced percentage of sand particles in the RC20 sample. These grains, characterized by their angular shapes and rough surfaces, could increase concrete strength by promoting better adhesion between particles [50,51]. It can be concluded that porosity decreases with increasing fines concentration. There-fore, it was found that marble fines clog the pores and provide a good interface between aggregate and paste. In addition, the RC0 reference concrete has acquired high porosity and absorption by immersion, due to the high content of RCA particles, which are characterized by the old cement paste with high porosity [40,43,44]. Omary et al. [52] demonstrated, using the SEM technique, a high-quality interface between the old paste enveloping the natural aggregates present in RA and the new paste. Subsequently, microcracks were detected in the ancient cement paste, probably caused by the process of RA crushing

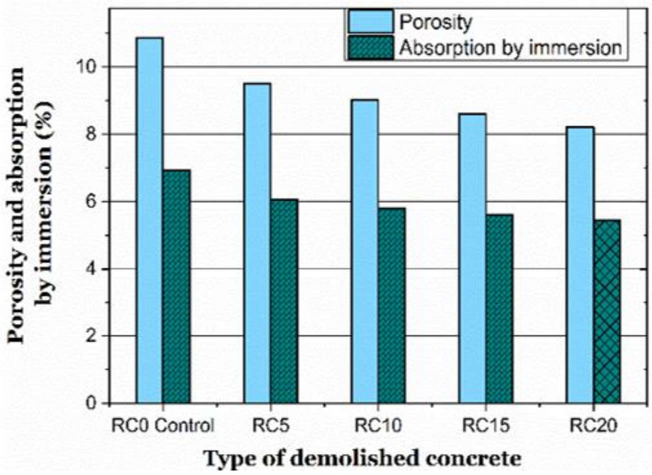


Fig. 10. Variation of porosity and water absorption by immersion as a function of marble fines percentage included in the RAC at 60 days

3.2.5. Softening Coefficient

The values presented in Fig. 11 show that all concrete formulations exhibit a softening coefficient exceeding 0.8. This finding indicates that all the studied samples are resistant to moisture, especially RC10 and RC15. For materials with a softening coefficient equal to or greater than 0.8 are considered to be water resistant especially in areas where moisture is a constant factor [53]. The obtained results for RC10 are consistent with the results of compressive strength and capillary water absorption. This proves how much the incorporation of 10% marble fines has reduced the maximum voids, and offered a better grain arrangement and interface between the grains and the cement paste.

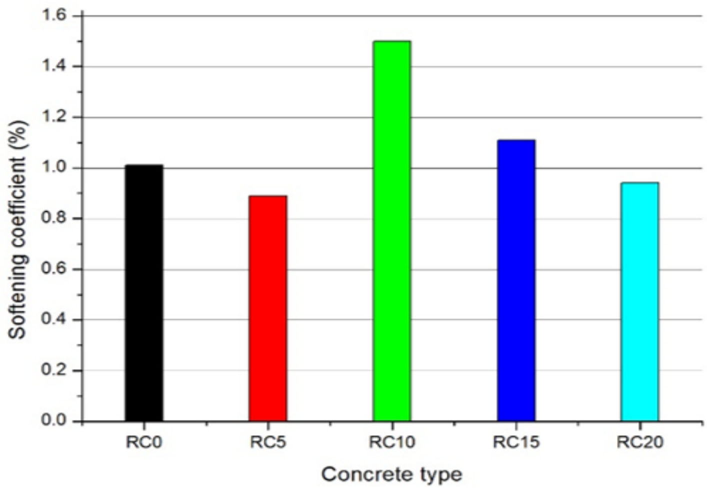


Fig. 11. Softening coefficient at 60 days

Fig. 12 illustrates the condition of cubic concrete specimens (10 × 10 × 10 cm), both dried and saturated, subjected to tests at 60 days to evaluate the softening coefficient, a key indicator of mechanical performance and durability. The dried specimens were tested to determine their compressive strength (R_{dry}), revealing significant cracking and fragmentation, indicative of failure under load. The water-saturated specimens (R_{sat}) exhibited deformations accompanied by scattered debris, highlighting the influence of moisture on compressive strength. The softening coefficient (K_{sof}) was calculated using Eq (5) by comparing the R_{dry} and R_{sat} values to assess the material's durability under varying moisture conditions. These results are critical for applications in water-exposed environments, ensuring long-term structural reliability.

Fig. 12. Specimens after testing for different formulations

3.3. Polynomial Regressions Generated Under the Effect of FM Variation in Concrete Based on Demolished Aggregates and Marble Fines

Several researchers have studied the Recycled Aggregate Concrete (RAC) adjusted with marble fines to find approximate relationships, which have allowed elaborating pseudo-exact expectations of some factors characterizing fresh and hardened concrete properties. The aim is to translate the relationships between the various factors into mathematical equations capable of predicting the RAC's physical-mechanical behavior. It was observed, in the first instance, that when increasing the fines content substituted with the fine aggregate of the fully demolished concrete, the fineness modulus decreases and consequently the fresh density and slump will also be increased [54]. For this purpose, two satisfactory relationships were deduced from the ANOVA analysis of variance, establishing two polynomial correlations between the density and slump of the different formulations as a function of the variation in fineness modulus. The first relationship is characterized by a second-degree equation, as illustrated in Fig. 13, and a correlation coefficient R^2 of 0.953. In addition, a second polynomial relationship of third order is shown in the same graph, matching the slump and the fineness modulus of R^2 equal to 0.984.

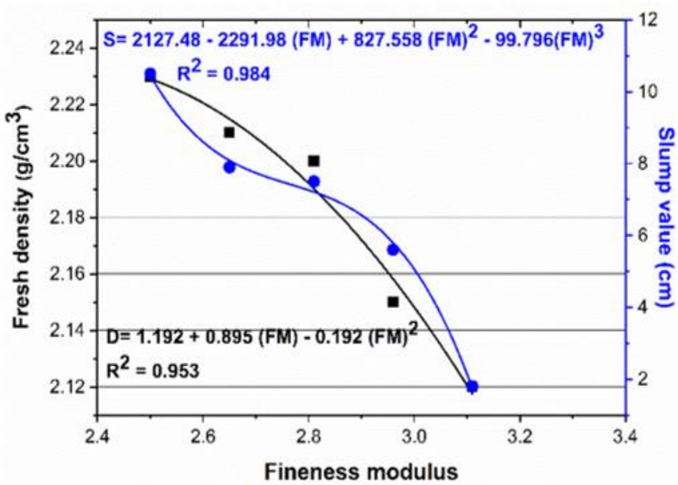


Fig. 13. Relationship between fresh density, slump and fineness modulus of RAC with and without marble fines

Therefore, it can be concluded that when the FM (Fineness Modulus) tends to half the range of the preferred sand of (2.2 – 2.8), the manufactured mix has obtained better fresh state properties of RAC with marble fines. Fig. 14 clearly shows another relationship deduced from the previous results (from Fig. 13) describing a high dependence of a third order linear regression and R^2 equal to 0.999. This approach is likely to be strongly supported in the case where the RAC is modified with a less absorbent material than the demolition RA.

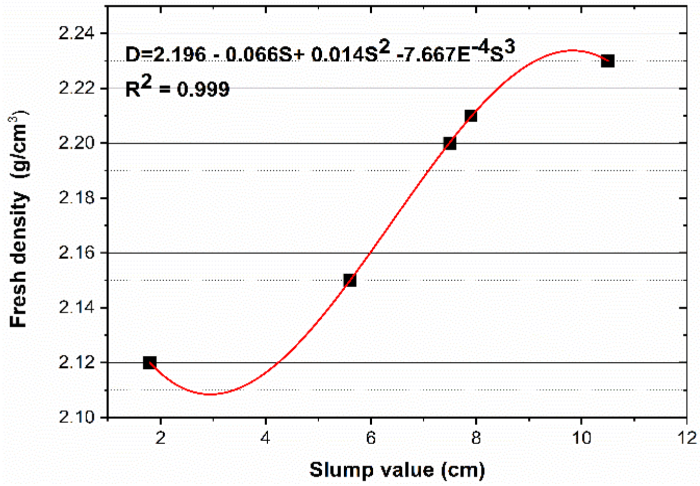


Fig. 14. Relationship between fresh density and slump of RAC with and without marble fines

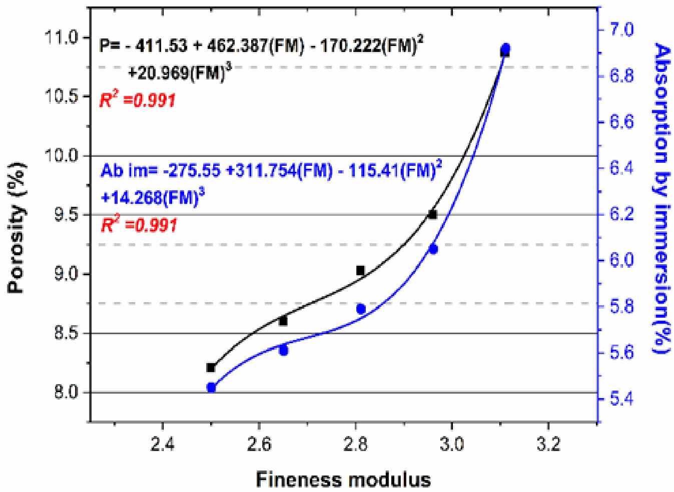


Fig. 15. Relationship between porosity, absorption by immersion and fineness modulus of RAC with and without marble fines

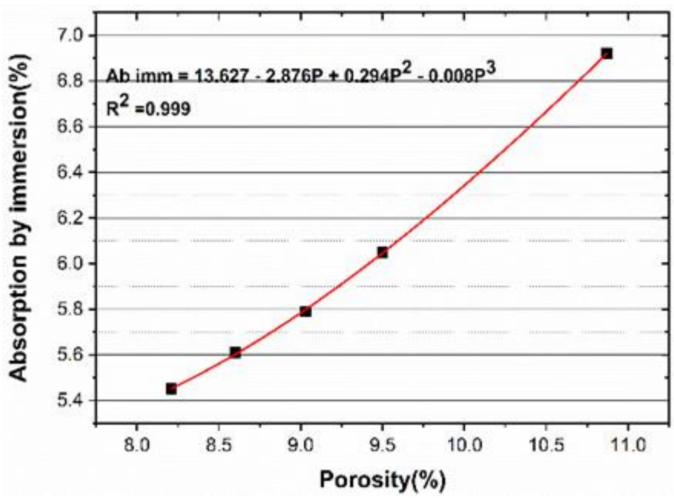


Fig. 16. Relationship between absorption by immersion and porosity of RAC with and without marble fines

Secondly, and concerning the two indicators of liquid transfer (porosity and water absorption by immersion), it was shown that when starting to replace the fine aggregates of the RS with marble fines, the two previous indicators were decreased as shown in Fig. 15. This finding has been approved by several researchers [55]. The two third order relationship equations shown in Fig. 15

have the same direction of functional variation, i.e., in the time when the fineness modulus increased progressively, the porosity and the amount of water absorbed also increased. In fact, the fines play a role in clogging the capillary spaces and offered a good interfacial transition zone, which subsequently increases the magnitude of the mechanical strengths. These two equations mentioned above provided us with a very good correlation coefficient with a value of 0.991. This statistical study allows us to observe another good correlation between the absorption by immersion and the porosity accessible to water, with a R^2 of 0.999 (Fig. 16). It was also found that the statistical prediction has a great interest in the modern science of building materials and subsequently in the advanced evaluation of a pathological state of the structures in cementitious materials.

4. ANOVA Analysis and Optimization by RSM

4.1. Rc and Rf Response Surface Models

The interaction effects of two factors on the mechanical properties of fines marbles reinforced recycled aggregates concrete (RAC) were specifically investigated and predicted: fines marbles (A), of hydration duration (B). These studies were carried out using an RSM in which the two responses, comprising compressive strength and flexural strength. Different polynomial mathematical regression models were used for each response, including linear, two-factor interaction (2FI), quadratic, cubic, and Quartic, as shown in Table 7. The quadratic model is the most relevant among the others, and demonstrated the highest possible correlation coefficients.

Compressive and flexural strength evaluations were performed using analysis of variance (ANOVA), as presented in Table 8. To determine the pertinence of the proposed models to the experimental data, we considered model accuracy analysis using F-values, P-values, and R^2-values. The results obtained from the ANOVA indicate that the models establish an adequate relationship between the independent factors and the responses. For an estimated mechanical test result to be considered significant, it must have a P-value of less than 0.05. In the case of the ANOVA results for Rc and Rf, all P-values were below 0.0001, confirming that the models are highly significant.

4.2. Final Equations in Terms of Coded Factors

The equation in terms of coded factors (A: % fines marbles and B: hydration duration) can be used to make predictions about the response for given levels of each factor (see Table 5). By default, high levels of the factors are coded as +1 and low levels are coded as −1. The coded equation is useful for identifying the relative impact of factors A and B on compressive and flexural strength values.

$$R_c = 36.36 + 0.1035A + 2.48B + 0.8816AB - 1.79A^2 - 2.42B^2 \tag{8}$$

$$R_f = 4.38 + 0.2438A + 0.579B - 0.0881AB + 0.2415A2 - 0.3645B^2 \tag{9}$$

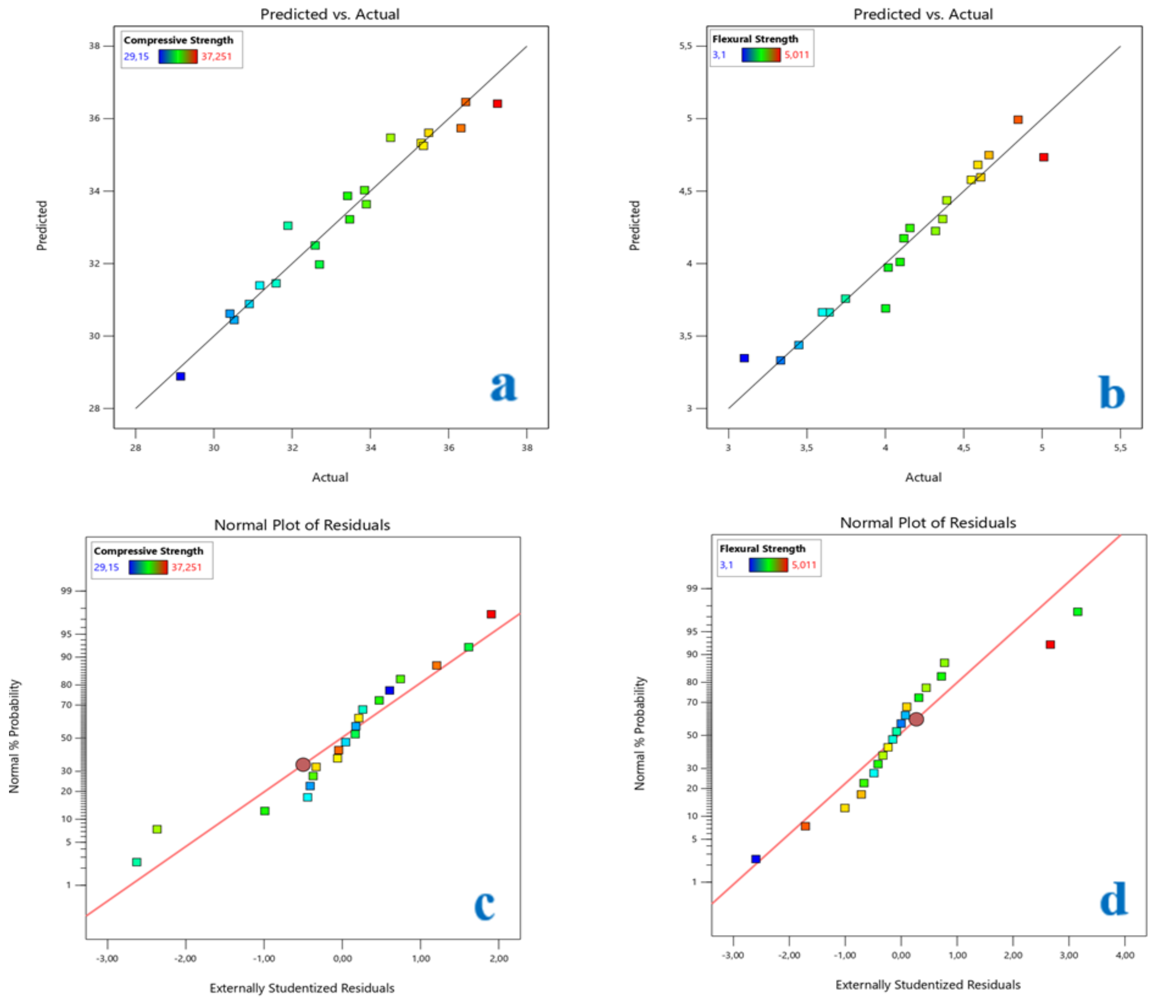
4.3. Rc and Rf Response Surface Plots

In this study, the independent variables B, B^2, AB, and A^2 were determined to be significant for compressive strength, whereas variable A was found to be insignificant. For flexural strength, variable B was identified as the most significant factor, while variables A, A^2, and B^2 were also deemed significant. However, the interaction term AB was found to be insignificant. Figs. 17a-17b show the relationship between experimental results and predicted values for compression and flexural tests respectively. The R^2, R^2_{adj} and R^2_{pred} values, all close to 1 according to Table 8, indicate excellent interrelationships between experimental results and predicted models. Model adequacy was also assessed by examining the dispersion of residuals, i.e., the difference between actual and predicted values, which should follow a normal distribution.

Figs. 17c-17d show that the residuals follow a linear normal distribution, confirming the suitability of the models. In addition, the residuals show a random and symmetrical dispersion around the control zero line, as can be seen in the plots of the residuals against the predicted values (Figs. 17e-17f). This uniformity of data variability also reinforces the validity of the models used. Fig. 18 shows the 2D response surface curves (Contour plots) for compressive and flexural strength as a function of the process variables. The curves were generated by plotting the response output as a function of two independent parameters (A: % fines marbles and B: hydration duration). Compressive strength and flexural strength were mainly affected by marble fines content and hydration time, as their linear relationship was significantly high at $p < 0.01$ (Table 8).

Table 7. Summary of Statistical Analysis for Compressive and Flexural Strength

	Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Compressive strength (MPa)	Linear	0.0003	0.5713	0.4641	
	2FI	0.1577	0.5995	0.3924	
	Quadratic	< 0.0001	0.9399	0.9169	Suggested
	Cubic	0.5644	0.9358	0.8006	
	Quartic	0.1959	0.9557	0.5845	Aliased
Flexural strength (MPa)	Linear	< 0.0001	0.7927	0.7342	
	2FI	0.3856	0.7902	0.7219	
	Quadratic	0.0005	0.9185	0.8359	Suggested
	Cubic	0.1503	0.9385	0.7266	
	Quartic	0.1852	0.9585	0.7234	Aliased



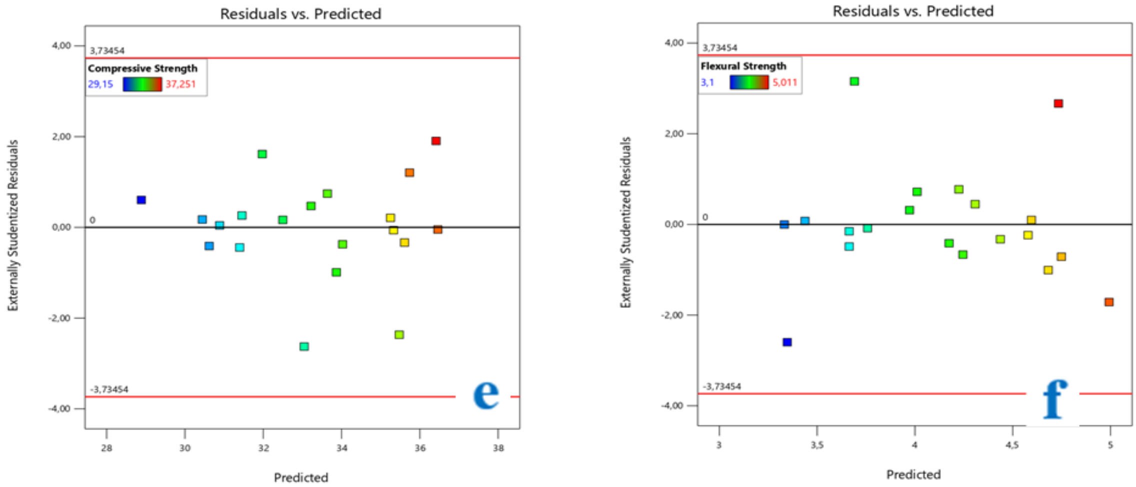


Fig. 17. Diagnosis of concrete compressive and flexural strength models by: Predictions vs. actuals, Normal probabilities vs. residuals and Residuals vs. predictions

The 3D response surface plots in Fig. 19 illustrate the interaction effect between marble fines content and hydration time on compressive and flexural strengths. It can be seen that each graph shows a significant decrease on both sides of the peak, suggesting that the compressive and flexural strengths of RAC concretes adjusted with marble fines initially increase with increasing marble fines content and hydration time, then decrease thereafter. Clearly, a low marble fines content is not conducive to improved compressive strength of RAC adjusted with marble fines, and an ideal percentage is found to be between 10% and 15%. However, the percentage of marble fines that favors enhanced flexural strength is between 15% and 20%. Fig. 19 reveals also that compressive and flexural strengths reached their maximum values when the marble fines content was adjusted to an appropriate proportion. Furthermore, it is important to note that the contribution of hydration time to strength development only becomes significant after a period of 28 days [56].

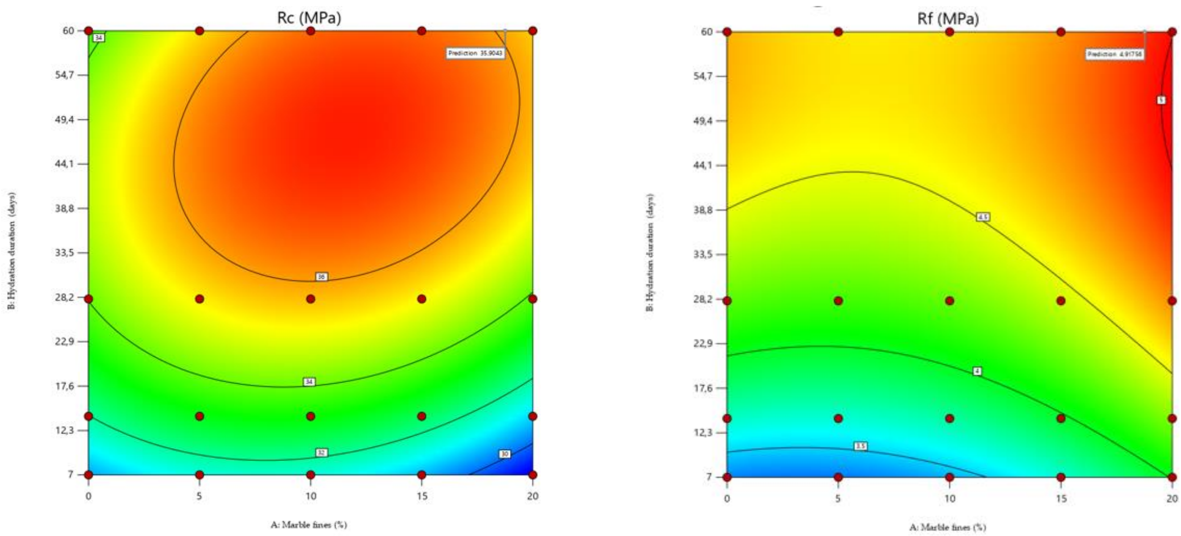


Fig. 18. Contour plots of response surface for Rc and Rf

The analysis of this ecological concrete using the RSM methodology, which is based on a central composite design (CCD), has made it possible to model the relationships between the percentage of fines of marbre (0–20%), the hydration period (7–60 days), and the compression and flexion strengths. A small difference between the R-carré values (for example, 0.95), and the R-carré adjusted values (0.93), indicates a high degree of reliability of the second-order polynomial model, which accurately captures the variability of strengths without undue complexity or dependence on superfluous variables. This observation validates the use of RSM to optimize environmentally friendly concrete formulations by forecasting in a feasible manner and validates the relevance of the factors selected, effectively expressing the variability of performances without using redondants.

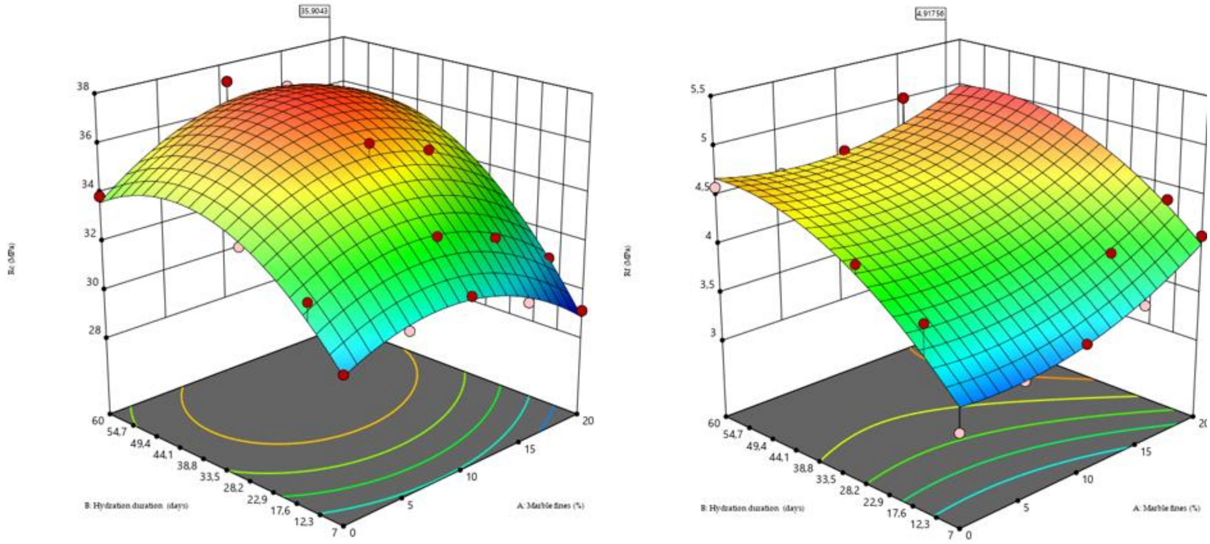


Fig. 19. 3D response surface representation RSM models for Rc and Rf

4.4. Optimization

To simultaneously optimize the responses, a numerical optimization technique utilizing desirability functions for each response was implemented. This method facilitates the identification of solutions that balance the various objectives of the problem effectively [57, 58]. The objective of this study was to maximize the mechanical properties, specifically compressive strength (Rc) and flexural strength (Rf), of recycled concrete incorporating marble fines. Consequently, it was critical to optimize these two responses concurrently, with both considered of equal importance. To accomplish this, two input factors—marble fines content (A) and hydration duration (B)—were evaluated within a range defined by the Central Composite Design (Table 9).

Marble fines, used as a partial substitute for sand or cement in concrete, have an incorporation range from 0-5% (lower limit) to 15-30% (upper limit), depending on the targeted performance (strength, durability, workability). At low dosage (0-5%), they act as fillers, improving compactness and workability without altering mechanical strength, as demonstrated by Alyousef et al. [59]. The upper limit, often set at 20% for structural concretes, is limited by reduced compressive strength and increased porosity beyond that, due to the low reactivity of fines [60]. In self-placing concretes, dosages up to 25% are possible with admixture adjustments, but durability may decrease [61]. These limits vary according to the particle size and purity of the fines, in line with standards such as ASTM C618. RSM makes it possible to optimize dosages (10-15% ideal) to balance performance and environmental impact, as validated by [62]. In this contribution we can take a percentage of marble fines altered between 5 and 20% with a 5% step (Table 9). The solution to this multi-objective optimization and its contour diagram are shown in Figs. 20-21. The results show that the optimum values for achieving a maximum desirability of 0.926 were a marble fines content of 18.75% and a hydration time of 60 days (Fig. 22). These values were determined to obtain the best mechanical properties for recycled concrete adjusted with marble fines. Desirability was achieved at a value of 0.926, demonstrating that the responses had been optimized. At this desirability, the two best response values for R_c (compressive strength) and R_f (flexural strength) were 35.90 MPa and 4.92 MPa respectively (Fig. 20).

The CCD-based RSM model for optimizing eco-concrete with marble fines is thoroughly validated through a rigorous multi-faceted approach, establishing it as a groundbreaking method for sustainable construction. Statistically, the model demonstrates exceptional reliability with an R^2=0.9557, adjusted R^2=0.9399, and a cross-validated Q^2 ≈0.85–0.90, underpinned by highly significant ANOVA results ($p < 0.0001$). Graphical diagnostics (Figs. 17–19) confirm adherence to assumptions, with residuals exhibiting normality (Shapiro-Wilk W > 0.9) and independence

(Durbin-Watson ≈2). Experimentally, the model accurately predicts strengths at the optimal condition of 18.75% marble fines and 60 days, yielding 35.9323 MPa (R_c) and 4.9155 MPa (R_f), with confirmation run errors of just 1.67% and 2.44%, well within experimental variability. A comparative analysis with studies evaluated by researchers [59,61] validates its predictions, while its environmental benefits—reducing waste and optimizing formulations—position it as a transformative solution. This validated model not only achieves optimal mechanical performance but also paves the way for eco-friendly, economically viable concrete production, meeting the construction industry's sustainability demands with exceptional accuracy and robustness.

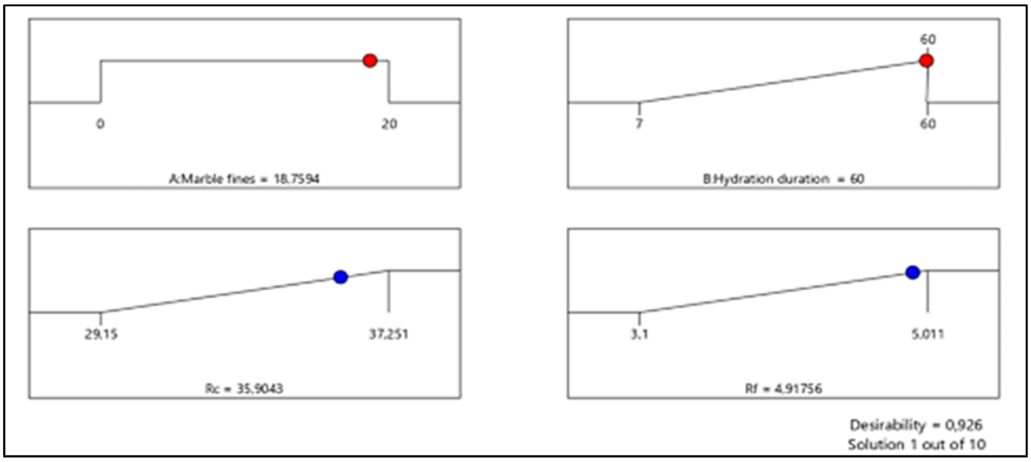


Fig. 20. Optimal solutions for concrete produced

Table 8. Analysis of variance of compressive strength and flexural strength responses for concrete

Source	Sum of Squares	DF	Mean Square	F-value	P-value	Remarks
1- Compressive strength (MPa)						
Model	94.71	5	18.94	60.42	< 0.0001	significant
A	0.098	1	0.098	0.3125	0.585	
B	70.59	1	70.59	225.19	< 0.0001	
AB	4.59	1	4.59	14.64	0.0019	
A^2	11.23	1	11.23	35.81	< 0.0001	
B^2	17.81	1	17.81	56.82	< 0.0001	
Residual	4.39	14	0.3135			
Cor Total	99.1	19				
SD = 0.5599				*R^2 =*	0.9557	
Mean = 33.31				*R^2 Adjusted =*	0.9399	
Coefficient of Variation = 1.68				*R^2 Predicted =*	0.9169	
Predicted Residual Sum of Squares (PRESS) = 8.23				*Adequate Precision=*	24.6935	
2- Flexural strength (MPa)						
Model	4.9	5	0.9796	43.84	< 0.0001	significant
A	0.5431	1	0.5431	24.31	0.0002	
B	3.85	1	3.85	172.31	< 0.0001	
AB	0.0458	1	0.0458	2.05	0.1743	
A^2	0.2041	1	0.2041	9.14	0.0091	
B^2	0.4036	1	0.4036	18.06	0.0008	
Residual	0.3128	14	0.0223			
Cor Total	5.21	19				
SD = 0.1495				*R^2 =*	0.9400	
Mean = 4.13				*R^2 Adjusted =*	0.9185	
Coefficient of Variation = 3.62				*R^2 Predicted =*	0.8359	
Predicted Residual Sum of Squares (PRESS) = 0.8551				*Adequate Precision=*	20.2852	

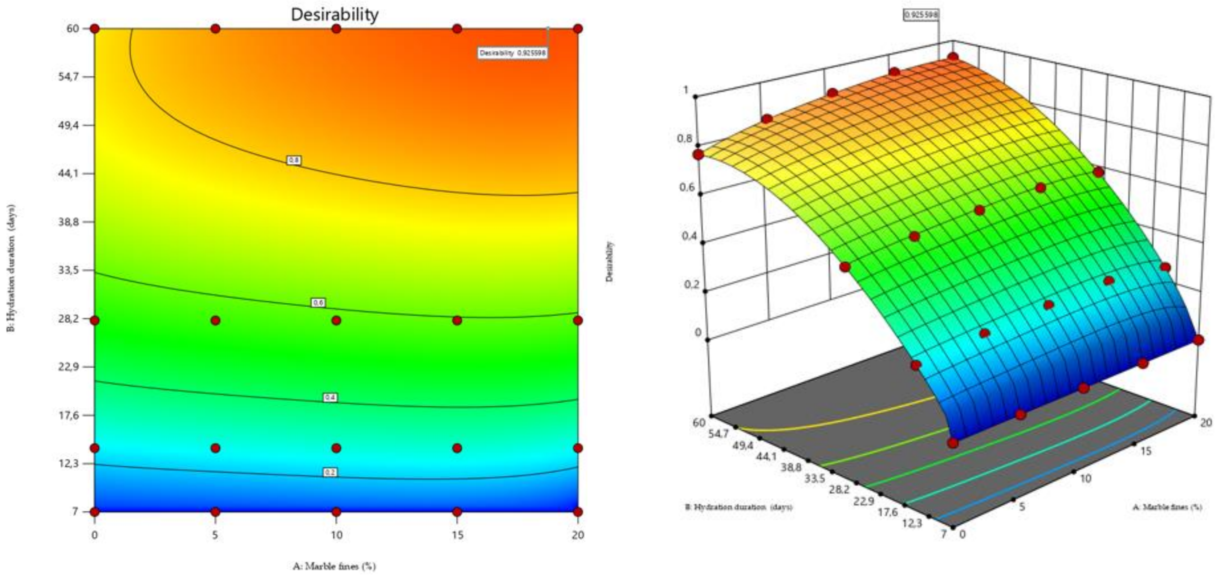


Fig. 21. 2D and 3D desirability function

Table 9. Goal and importance of concrete with their response's constraints.

Name	Goal	Lower Limit	Upper Limit	Importance
A: Marble fines	is in range	0	20	5
B: Hydration duration	is tarjet=60	7	60	5
R_c	maximize	29.15	37.251	5
R_f	maximize	3.1	5.011	5

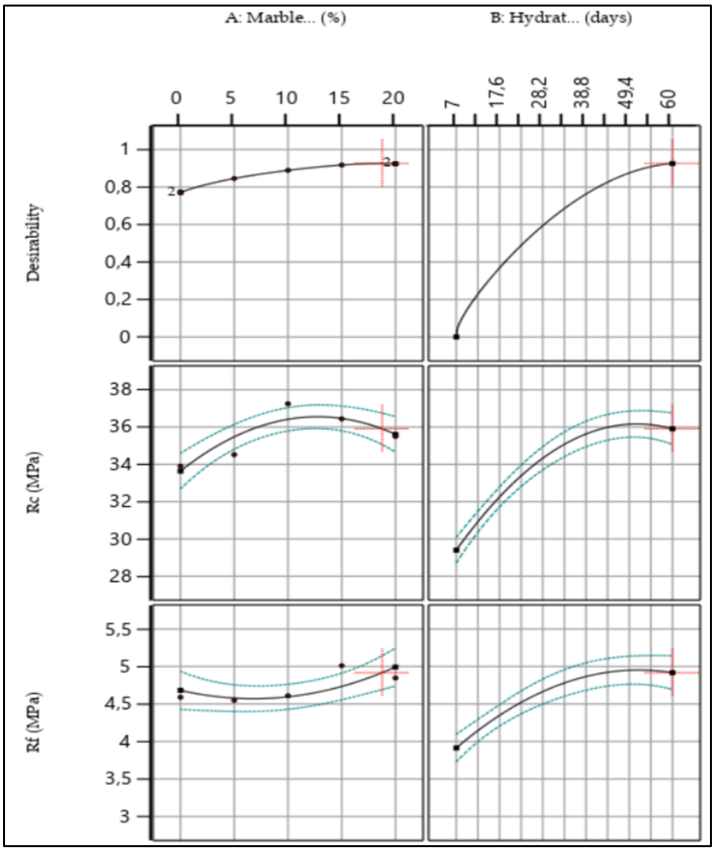


Fig. 22. Desirability of concrete studies by RSM

5. Conclusion

This study analyzed the effect of adding marble fines on the physical-mechanical properties of concrete made entirely from recycled materials. The experimental results and the RSM model-based CCD design led to the following conclusions:

- The incorporation of marble fines in the manufacture of concrete from recycled demolition materials, replacing fine sand from the demolition process, significantly improves workability and promotes better densification of the granular structure.
- A lower recycled demolition sand content increases slump as fine marble particles replace coarser sand, reducing internal friction and improving workability, resulting in a smoother, more fluid mix.
- Marble fines have a positive influence on the physical properties of concrete based on recycled aggregates, such as capillary water absorption and water accessible porosity.
- Porosity and water absorption values decrease with increasing percentage of marble fines in all mixes. Based on the value of the softening coefficient, the best substitution is the fine marble 10%.
- The use of marble fines 10% and 15% was advantageous for all physical-mechanical characteristics of ordinary concrete which consists of pure demolition aggregates.
- Polynomial regressions were translated into polynomial equations capable of giving a prediction of the physical behavior of RAC.
- The use of response surface methodology (RSM) proved to be an effective and beneficial approach to optimizing the design parameters of eco-concrete contains marble fines. The statistical results of the ANOVA confirmed the validity of the strength models selected from the RSM, demonstrating their satisfaction.
- The Response Surface Methodology effectively optimized eco-concrete design parameters using marble fines, with its efficacy confirmed through robust statistical and graphical validations. ANOVA results ($p < 0.0001$) validated the strength models, while predicted versus actual strength plots and response surface trends (peaking at 10–20% marble fines) affirmed the model's predictive accuracy. These findings highlight RSM's reliability for sustainable concrete optimization within the studied design space.
- Mathematical equations, inspired by Composite Central Design (CCD), optimize the use of marble fines and immersion time to significantly improve the mechanical strengths of cementitious products made entirely from recycled aggregates.
- The optimum values of the design variables obtained were as follows: marble fines of 18.75% and a hydration duration of 60 days, according to the best compressive and flexural strengths of 35.90 MPa and 4.92 MPa, respectively.
- The technical data resulting from this study will contribute to the design of environmentally-friendly, sustainable and economically viable concretes, adapted to the construction requirements of tomorrow.

Incorporation of marble fines into concrete based on recycled demolition aggregates significantly improves the physical-mechanical characteristics of concrete, if the appropriate mix design is used. Therefore, it would significantly reduce the environmental impact of concrete waste.

Nomenclature

RAC	Recycled aggregates concrete	RCA	Recycled concrete aggregates
ANOVA	Analysis of variance	RS	Recycled sand
RG	Recycled gravel	$RS_{i\%mf}$	recycled sand of i% marble fines
ASTM	American Society for Testing and Materials	W/C	Water/cement ratio
$RC_{i=0,5,10,15,20}$	Recycled concrete of i% marble fines	RFA	Recycled fine aggregates
RA	Recycled aggregates	FM	Fineness modulus
RSM	Response surface methodology		

Acknowledgements

This work was supported by the LEVRES laboratory, University of El Oued and the DGRSDT-Algeria.

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