

## STATISTICAL ANALYSIS OF 3-POINT BENDING PROPERTIES OF POLYMER CONCRETES MADE FROM MARBLE POWDER WASTE, SAND GRAINS, AND POLYESTER RESIN

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*The mechanical performance of concrete polymer beams subjected to 3-point bending was investigated. The polymer concrete incorporates marble powder waste and quarry sand. The results obtained showed that the type of sand, and amount of marble powder and sand aggregate affected the resistance of the polymer concrete beams significantly. The marble waste increased their bending strength by reducing the porosity of polymer concrete.*

### 1. Introduction

Polymer concrete (PC), also known as synthetic-resin concrete [1], is a composite material in which the monomer (binder) undergoes polymerization (curing) after the addition of additives, catalysts, and accelerators [2]. Coarse and fine aggregates, such as crushed stone, sand, gravel, and fly ash, are widely used as mineral fillers in the production of PCs. In order to improve the mechanical properties of PCs, minerals such as marble, basalt, and quartz can be used instead of sand. Burnt rice balls can also be used as reinforcing fillers [3-5].

PCs are usually made with a thermosetting resin as the binder for natural or artificial aggregates [6]. The first applications of PCs relate to the 1950s. The excellent properties exhibited by these materials have favored a rapid increase

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in their application. The fast curing of PCs, excellent bonding to concrete and the reinforcing steel, and a high strength and durability make them a very attractive repair material despite their poor thermal resistance at temperatures exceeding 150°C [7]. As a mortar, PC can be deposited with thicknesses less than 10 mm. PCs are also widely used for bridge coatings and industrial floors because of their rapid curing, very low permeability, and high resistance to chemical substances and freeze-thaw cycles. PCs can also be employed in house and building fronts [8-12]. The main advantage of PCs over the traditional concrete is their ability to integrate recycled waste products because of the isolating nature of the resin matrix [13]. Industrial waste, such as marble and granite powders, fly ash, slag, wood shavings, granulated cork and tire rubber, foundry sands, as well as granules of plastic materials from crushed waste electrical cables have been used with success to replace the feed components and mineral aggregate in concrete [13-21]. Large quantities of waste are produced annually in different countries. Marble and granite waste pose serious environmental threats by polluting the soil and water. Currently, ways are being examined to recycle the waste into a durable material, such as polymer concrete. Saboya et al. [22] and Gencil et al. [23] reported that the amount of cutting waste from sawing and polishing of Brazilian decorative stones reached 20-25% of the total volume of the raw material. Several studies have also addressed the recycling of marble powder waste into Portland concrete cement [21-26]. The use of marble waste in PC components is considered by Tawfik and Eskander [14], where the granular structure of a polymer concrete made from polyethylene terephthalate (PET) recycled resin, marble waste, and basalt is optimized. The polymer concrete obtained showed rapid hardening, acceptable physical performance, and good chemical properties. Martinez-Barrera and Brostow [27] studied the influence of gamma radiation and marble particle size on the compression properties and dynamic elasticity modulus of PC. An optimization of the PC granular skeleton was carried out by Elalaoui et al. [7]. The resulting granular mixture showed good compactness and minimum voids.

The aim of this study was to explore the possibility of using the marble powder waste (MW) from the local Algerian quarry sand (SW) as a substitute for the marketed sand (MS) imported from abroad. An ANOVA variance analysis was performed to validate the experimental results obtained. The F ANOVA test allowed the verification of effects significantly different from zero [28].

## 2. Experimental Procedures

### 2.1. Constituents of PC

This work is focused on a synthetic concrete made from a granular material with a polymeric matrix. The matrix was an unsaturated 716.09 polyester resin manufactured by Technobell London. Two kinds of composites were prepared with 14 wt.% of the resin. One composite comprised a marketed sand (MS) of density 1.524 g/cm<sup>3</sup> and the same marble powder waste (MW) of density of 1.425 g/cm<sup>3</sup>. The other one contained quarry sand waste and (SW) of density 1.675 g/cm<sup>3</sup> and the same marble powder. The choice of 14 w.% resin was based on the work by Elalaoui et al. [7], who reported that the porosity and the bending strength were optimum at this content of polymer. Gorninski et al. [2] used 12% of orthophthalic polyester and 13% of isophthalic polyester for polymer concrete.

The SW was washed and steamed in an oven at 105°C for 24 h to reduce the humidity and ensure good bonding between the aggregates and the polyester matrix, but the MS was only steamed under the same conditions. A particle size analysis according to the NFP18-560 standard indicated that the diameter of particles of both sands varied from 1 to 3 mm, but that of the marble waste — from 0.02 to 1.4 mm. Figure 1 shows the particle size distribution of these two aggregates. Design of a durable polymer concrete with adequate physical and mechanical properties requires optimization of its granular skeleton to minimize the porosity. To this end, seven formulations of composites were investigated, which are indicated in Table 1.

The polymer concrete was made by mixing the sand with marble waste powder to obtain a mixture of aggregates that was then gradually introduced in the polyester resin, premixed with a solution of methyl ethyl ketone peroxide in

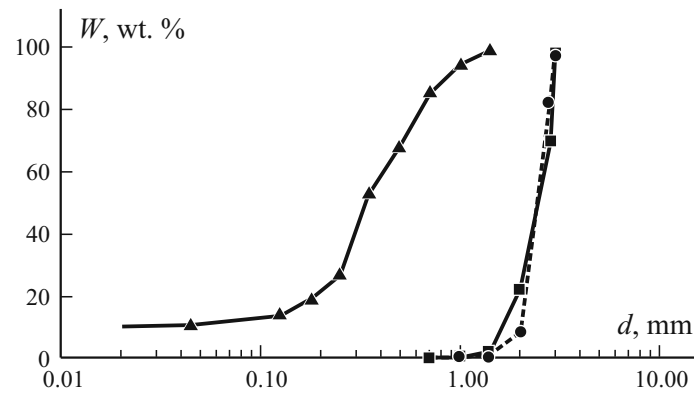


Fig.1. Weight percentage  $W$  of MS ( $\blacklozenge$ ), MW ( $\blacktriangle$ ), and SW ( $\blacksquare$ ) particles of various sizes  $d$ .

TABLE 1. PCs Made Using Marketed Sand (MS) and Quarry Sand Waste (SW)

Composition		Resin	Sand wt. %	Marble waste (MW)
MS	SW			
MS0 /MW86	SW0 / MW86	14	0	86
MS16/ MW70	SW16/ MW70	14	16	70
MS26/MW60	SW26 /MW60	14	26	60
MS43 /MW43	SW43 /MW43	14	43	43
MS60 /MW26	SW60/ MW26	14	60	26
MS70/MW16	SW70/ MW16	14	70	16
MS86/ MW0	SW86 /MW0	14	86	0

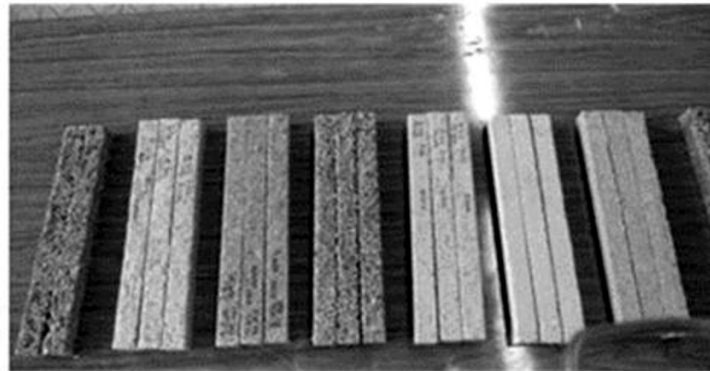


Fig. 2. Polymer concrete samples with different formulations.

dimethyl phthalate (AKPEROX A.60) as catalyst and cobalt ethylhexanoate in aliphatic ester as an accelerator (1% each), while stirring with a spatula.

The resulting polymer concrete was poured into two prismatic molds, each able to contain seven specimens of dimensions  $25 \times 25 \times 300$  mm according to the ASTM C580.02 standard. The filling was done in two steps: half-filled molds were first placed on a vibrating table to obtain good compaction of the polymer concrete, and then the filling was completed. Wax as a liner was used on walls of the molds to facilitate demolding, which was performed after 24 h (see Fig. 2). The specimens were dried at room temperature for at least seven days before testing.



Fig. 3. Static bending test.

TABLE 2. Bulk Densities of Different Formulations

Sand*	$W_M$ , wt. %						
	0	16	26	43	60	70	86
SW	2062	2174	2242	2257	2266	2267	2192
MS	2082	2390	2432	2417	2241	2236	2192

\*Weight fraction of SW and MS = 86% – marble weight fraction.

### 2.3. Experimental procedures

Three-points bending static tests (Fig. 3) were performed in a laboratory of the University of Guelma using a universal servoelectric testing Zwick/Roell Z005 machine with a 5-kN load cell and displacement rate of 3 mm/min. The machine was controlled by a computer allowing data acquisition by a testXpert V10.11 software. The bending tensile strength was calculated, according to ASTM C580.02, from the formula

$$\sigma_L = 3Pl / (2bh^2), \quad (1)$$

where  $P$  is the breaking load,  $l$  is the distance between supports, and  $b$  and  $h$  are the width and height of specimen. Four specimens were tested for each formulation under ambient temperature (25°C) at a 60% humidity.

## 3. Results

### 3.1. Experimental data

Knowledge of the porosity is essential for any technical work with granular materials. The water-accessible porosity was determined using a hydrostatic balance, according to the NF P18-459 standard. The porosity  $\Pi$  was calculated from the mass of the specimens measured in saturated air,  $M_{air}$ , in water,  $M_{water}$ , and oven-dried at 50°C  $M_{dry}$ , by using the equation

$$\Pi (\%) = 100 (M_{air} - M_{dry}) / (M_{air} - M_{water}). \quad (2)$$

In construction materials, the porosity is generally measured by using the Archimedes method, from which the apparent densities of specimens are also obtained. The bulk densities and porosities (measured according to the NF EN 18-459 standard) obtained for the SW and MS specimens are presented in Table 2.

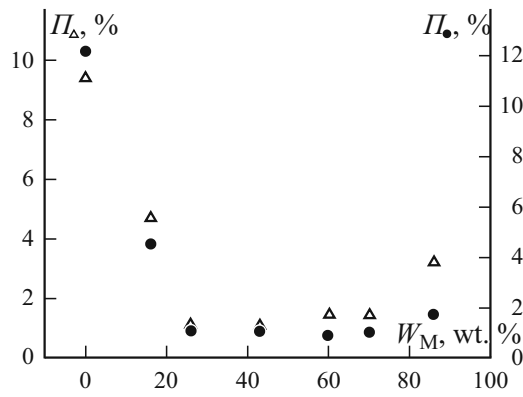


Fig. 4. Porosities of specimens with SW,  $\Pi_{\circ}$ , and MS,  $\Pi_{\Delta}$ , versus marble weight fraction  $W_M$ .

TABLE 3. Mechanical Characteristic of Resin

Source	Tensile			Flexural		
	Strength, MPa	Maximum strain, %	$E_t$ , GPa	Strength, MPa	Maximum strain, %	$E_b$ , GPa
Present study	$29.36 \pm 2.87$	$2.25 \pm 0.24$	$12.128 \pm 2.04$	$81.74 \pm 11.08$	$2.56 \pm 0.52$	$3.33 \pm 0.25$
Technobell [29]	50–70 ISO R 527	4–5 ISO R 527	3200–3600 ISO R 527	70–90 ISO 178	–	–

TABLE 4. Mean Values of the Bending Strength and Maximum Displacements of Different Formulations

Source	Formulation	Strength, MPa	$\Delta$ , mm	$E_b$ , GPa
Present study	MS0/MW86	$28.49 \pm 1.94$	$0.717 \pm 0.083$	$21.10 \pm 1.97$
	SW0/MW86	$28.49 \pm 1.94$	$0.717 \pm 0.083$	$21.10 \pm 1.97$
	MS16/MW70	$32.68 \pm 1.32$	$0.756 \pm 0.096$	$19.55 \pm 2.80$
	SW16/MW70	$32.89 \pm 2.29$	$0.710 \pm 0.081$	$20.86 \pm 2.80$
	MS26/MW60	$34.54 \pm 2.06$	$0.726 \pm 0.010$	$19.96 \pm 1.80$
	SW26/MW60	$31.89 \pm 1.69$	$0.677 \pm 0.023$	$20.92 \pm 0.78$
	MS43/MW43	$35.19 \pm 1.75$	$0.674 \pm 0.014$	$23.00 \pm 1.40$
	SW43/MW43	$29.06 \pm 0.34$	$0.766 \pm 0.100$	$16.52 \pm 1.93$
	MS60/MW26	$37.98 \pm 1.06$	$0.663 \pm 0.043$	$25.90 \pm 1.80$
	SW60/MW26	$25.71 \pm 1.24$	$0.667 \pm 0.032$	$12.58 \pm 1.08$
	MS70/MW16	$29.38 \pm 2.20$	$1.755 \pm 0.391$	$5.23 \pm 2.60$
	SW70/MW16	$18.07 \pm 1.68$	$0.946 \pm 0.224$	$3.91 \pm 3.70$
	MS86/MW0	$12.57 \pm 3.34$	$1.332 \pm 0.859$	$7.60 \pm 5.0$
	SW86/MW0	$12.00 \pm 0.16$	$1.278 \pm 0.149$	$3.08 \pm 2.90$
Shokrieh et al. [30]	MS75	19.69	2.96	–

The maximum porosities, 12 and 9%, were found for specimens prepared with SW and MS containing no marble powder (Fig. 4). With growing marble weight fraction  $W_M$ , the porosity decreased and became almost constant for formulations containing 26 to 70% of marble: 0.9–1.10% for the SW specimens and 1.09–1.45% for the MS ones. A slight increase in porosity (2.61%), however, was observed for specimen made completely with marble.

The mechanical properties of the resin alone (MS0/MW0) in tension and bending are shown in Table 3. The characteristics obtained from the tests are similar to the ones of cured unreinforced polyester resin 716.09 manufactured by Technobell London [29] and used in the manufacture of polymer concrete pipes (MAGHREB Pipe Industry M'sila, Algeria).

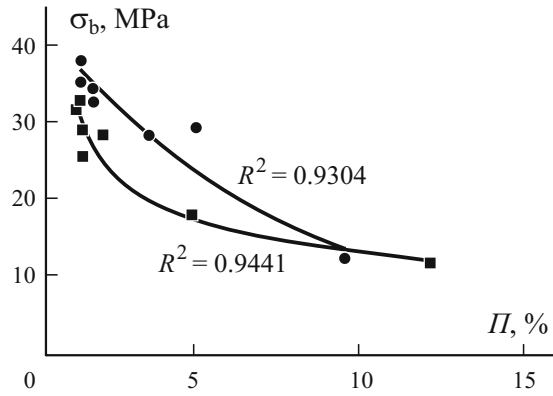


Fig. 5. Bending strength  $\sigma_b$  of PCs with MS (●) and SW (■) versus porosity  $\Pi$  .

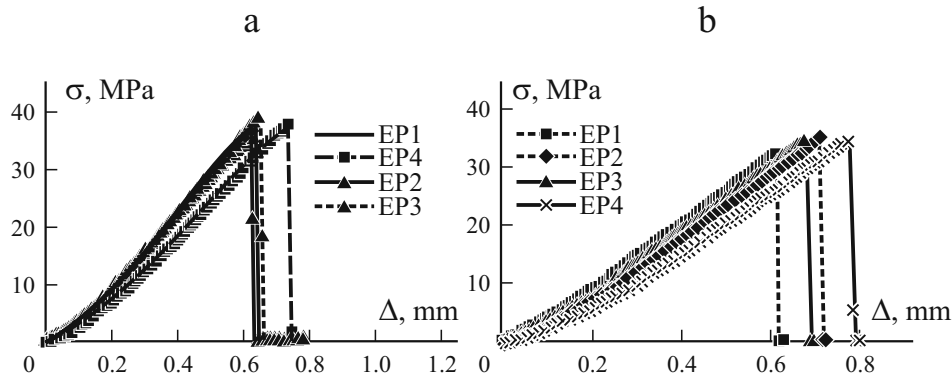


Fig. 6. Stress–displacement curves  $\sigma$ – $\Delta$  for various MS60/ MW26 (a) and SW16 /MW70 (b) specimens in 3-point bending.

Results of all bending tests performed, together with their standard deviations, are given in Table 4, where they are also compared with those found by Shokrieh, et al. [30]. In the latter reference, specimens were produced using a mixture with 25% resin and 75% fine silica sand with a maximum grain diameter of 5 mm.

The polymer concrete in [30] had an average bending strength of 19.69 MPa and a maximum displacement of 2.96 mm. The specimens obtained in this study showed a broad range of performance, with the lowest strength of 12 MPa for specimens made only with sand to the maximum of 37.98 and 32.89 MPa obtained with 26 and 70% of marble powder in specimens made with the marketed sand and quarry sand waste, respectively. The reason behind this increase in the bending strength was the significantly reduced porosity. The lowest maximum displacement of 0.663 mm was obtained for the MS60/MW26 composite, but the highest one, equal to 1.755 mm, was found for MS70/MW16. The maximum displacement of 2.96 mm obtained by Shokrieh et al. [30] is much greater than that in the present work. This can be explained, on one hand, by the higher proportion of resin used — 25% instead of 14 % in our case, and on the other hand, by the high elongation at break of the resin used, — 4% instead of only 2.56% in our work.

Figure 5 shows the bending strength  $\sigma_b$  as a function of porosity  $\Pi$  . A decrease in  $\sigma_b$  with increasing porosity is clearly seen.

Figure 6 depicts stress–displacement curves for the best PC formulations, MS60/MW26 and SW16/MW70. Table 4 shows a remarkable dispersion of the stress at failure ( $CV = 28\%$ ) between the different formulations of PC. The main effects of each factor and their interactions can be investigated by assessing the level of the average response using the analysis of variance (ANOVA).

TABLE 5. Variance Analysis of Different Formulations with MS and SW

Source	DF	<i>P</i> -value	Formulations with MS			Formulations with SW		
			SS	SM	<i>F</i> -value	SS	SM	<i>F</i> -value
Formulation	6	0.00	1699.2	283.2	56.59	1418.3	236.4	93.61
Error	21		105.1	5.00		53.03	2.52	
Total	27		1804.3			1471.4		

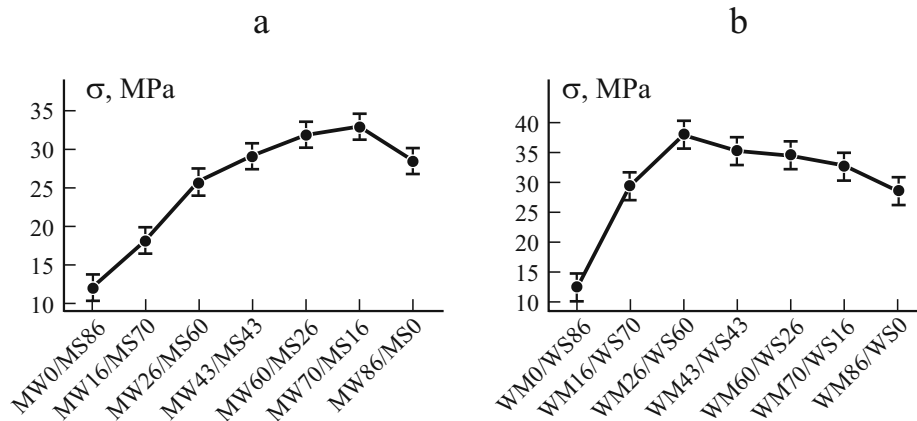


Fig. 7. Curves representing the values of stress  $\sigma$  for various formulations: (a) with MS and MW (a) and (b) with SW and MW.

### 3.2. ANOVA

The analysis of variance of experimental results for the samples prepared with MS and SW is presented in Table 5. The ANOVA results are listed in terms of degrees of freedom (DF), sums of squares (SS), squares of mean values (SM), Fisher test ratios (*F*-values), and *P*-values. The calculated values allow an assessment of the relative importance of each test factor. The Fisher test allows one to find out which effects are significantly different from zero [28]. The *F*-critical value ( $F_{crit}$ ) can be found in the *F* Snedecor table. If *F* is smaller than  $F_{crit}$ , the zero hypothesis is accepted, which means that the groups considered are not significantly different.  $F_{crit}$  was determined at a significance level of 5%, which is commonly used in practice [28].

As the *P*-value of the *F* test the strengths of MS and SW specimens ( $F = 56.59, 93.61$ , respectively is less than 0.05 above  $F_{crit} = 3.23$ ) it can be concluded that the difference between their average strength is statistically significant at a 95% confidence interval. The zero hypothesis  $H_0$  was therefore rejected.

## 4. Discussions

### 4.1. Effect of marble powder waste on the bending strength

Results of the experimental tests performed (Fig. 7) show that a partial substitution, up to 70%, of marketed sand aggregates (MS) or quarry sand waste (SW) by marble powder waste (MW) gradually increased the bending strength. Above this value, the strength decreased due to the increasing porosity. For the first type of polymer concrete, with MS, the highest bending resistance exhibited the MS60/MW26 formulation — with 26% MW, its bending strength was 202% of that of the basic formulation containing no marble. For the other types of SW polymer concrete considered, the best formulation was SW26/MW70 with 70% MW, showing a bending strength 174% of the strength of the basic formulation (Table 4). The vari-

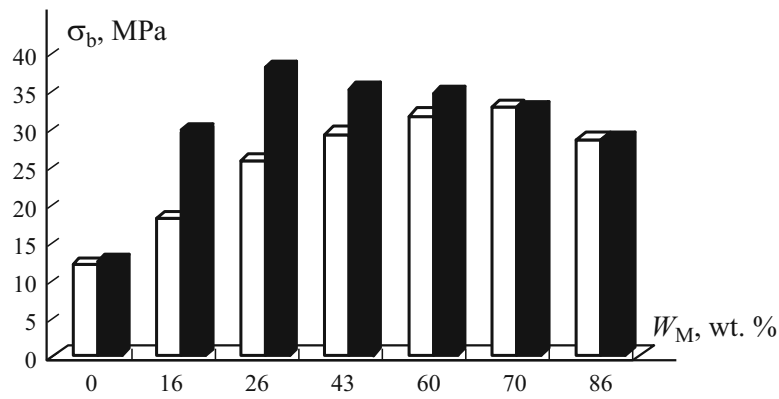


Fig. 8. Bending strength  $\sigma_b$  of SW ( $\square$ ) and MS ( $\blacksquare$ ) specimens versus weight content  $W_M$  of MW.

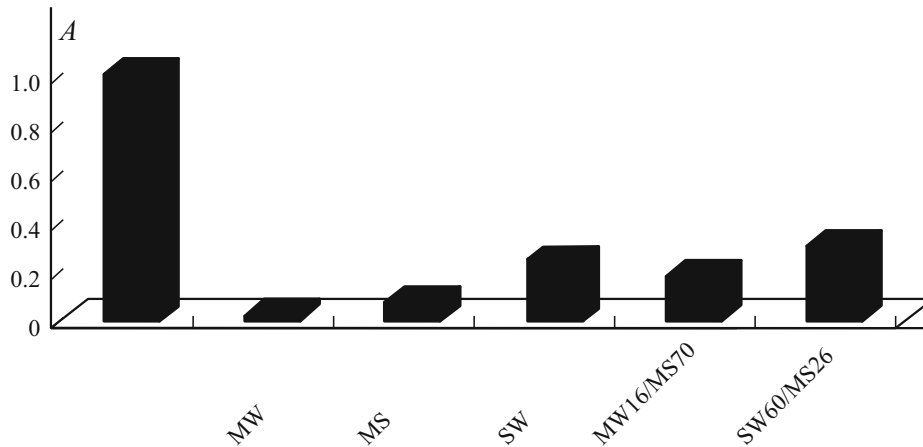


Fig. 9. Comparison of costs for different constituents of PC and their best formulations.

ability of the results is due to the granularity induced by the varying content of marble in the granular skeleton. The growth in the bending strength when the content of MW increased to 70% was caused by the reduction in porosity: from 12 to 0.9% for the SW specimens and from 9 to 1.09% for those with MS.

#### 4.2. Substitution of marketed sand (MS) by quarry sand waste (SW)

Figure 8 shows the bending strength  $\sigma_b$  of PCs with MS and SW versus marble content in them.. The histogram shows a significant increase in the bending strength with increasing marble content. The best formulation of PCs using MS (MS60/MW26) had by 15% higher bending strength than SW16/MW70. The best formulation of the PCs fabricated with SW was that containing 70% MW, but the best one with MS had only 26% MW.

A cost comparison was also performed between the two best formulations to determine the most economically viable type of polymer concrete (Fig. 9). Replacing the marketed sand by sand waste and mixing with MW can indeed provide an environmentally sustainable and economically viable PC material with acceptable bending properties. This material is also less expensive than the baseline one because of the high content of marble powder.



## 5. Conclusion

Fourteen formulations of PC with different content of marble powder waste (MW) and marketed sand (MS) replaced by waste quarry sand (SW) have been investigated, and their effect on the bending strength of beams has been evaluated. Based on the results obtained, the following conclusions can be drawn.

- In 3-point bending, the stress–displacement relation was nearly linear or quasi-linear up to failure.
- The incorporation of marble powder increased the density of PC by decreasing its porosity.
- ANOVA showed that the  $P$ -value of  $F$  test was smaller than 0.05, indicating that the differences between the bending strengths of PCs with different content of marble powder and aggregates were statistically significant.
- A partial replacement of the marketed sand aggregate with marble powder waste increased the bending strength of PC by 202% (for MS60/MW26) compared with that of PC with only the marketed sand (MS86/MW0). Similarly, replacement with the quarry sand waste (SW) increased this strength by 174% (for SW16/MW70);
- The maximum strength for the polymer concrete with SW and MW was only by 15% lower than that featured by the specimens with MS and MW. The polymer composites proposed provide a low-cost environmentally friendly material, made with marble powder and sand waste, exhibiting an acceptable flexural resistance.

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