Influence of Crushed Corn Cob Mass Percentage on the Compression Breaking Strength of Composites with Hybrid Matrix Based on Dammar Resin

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This study investigated the effect of crushed corn cob reinforcement on the compressive strength of composite materials with a hybrid matrix based on dammar (60%) and a synthetic epoxy (Resoltech 1050 with 1058s hardener). While previous research has explored mechanical and chemical properties of such composites, as well as the role of dammar resin, the specific impact of crushed corn cob on compressive strength had not yet been addressed. Materials with reinforcement mass fractions between 50% and 67% were fabricated, each with 15 samples. Power Analysis confirmed the sample size was statistically valid. A null hypothesis—stating that crushed corn cob has no significant influence on compressive strength—was tested and rejected ($p < 0.05$) using one-way ANOVA. Welch ANOVA confirmed the result ($F_w > 2.49$), and Kolmogorov-Smirnov tests showed data normality ($p > 0.05$). Post hoc ANOVA with Bonferroni correction confirmed significant differences between groups. The key finding was that beyond 66% crushed corn cob content, the materials lose engineering relevance due to inadequate compressive strength.

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INTRODUCTION

Biomass refers to the biodegradable portion of agricultural and organic waste, including plant residues, manure, and household food scraps. As a form of waste, it has been explored for reuse in various industries—for example, using straw and stalks as bioenergy sources in renewable energy production (Caicedo *et al.* 2016; Erdiwansyah *et al.* 2021).

Corn cobs, an agricultural biomass residue, remain underutilized in industry. Their most common application is in the production of fuel briquettes, though this typically involves torrefaction, which leads to energy losses (Erdiwansyah *et al.* 2021; Ibitoye *et al.* 2023; Oladosu *et al.* 2023). Another promising use is as a feedstock for biocoke, offering a renewable alternative to fossil fuels (Gani *et al.* 2023). Thoreson *et al.* (2014) analyzed densification parameters—such as compression pressure, moisture content, particle size, and material composition—for briquettes made from corn residues, including chopped cobs, and found that briquette quality improved with a higher proportion of corn cob in the mix. Corn cobs can also be used to produce bioethanol. Sewsynker-Sukai and Gueguim

Kana (2018) showed that simultaneous saccharification and fermentation offers high yield and efficiency while reducing production costs.

To reduce the carbon footprint, eco-friendly concrete has gained traction in construction. Grădinaru *et al.* (2021) assessed sunflower stalks and corn cobs as plant-based aggregates, noting slight decreases in mechanical and thermal properties with corn cob inclusion. Pinto *et al.* (2012) evaluated crushed corn cob in lightweight concrete, finding it suitable for non-structural use due to its low density and good insulation. Cunha *et al.* (2015) showed that corn cob combined with Portland cement can be used in concrete masonry blocks for both interior and exterior applications. Other applications of corn cob as a component in concrete production can also be found in the works of Adesanya 1996, Bheel *et al.* (2021), Binci *et al.* 2008, Mujedu et al. 2014, Oancea *et al.* (2018), and Șerbănoiu *et al.* (2022).

Corn cob can be used to obtain value-added products including hemicellulose, cellulose, and lignin. Fialho *et al.* (2023) developed eco-friendly extraction methods using organosolv and alkaline delignification after autohydrolysis, supporting its use in biorefineries. Another application is in agriculture where Deenik and Cooney (2016) combined corn cob with sewage sludge, enhancing plant growth and reducing soil Mn toxicity. In the circular economy context, Santolini *et al.* (2021) explored reusing corn cob for pellets and abrasive materials, showing a lower environmental impact compared to conventional products. Kumaravel *et al.* (2024) synthesized activated carbon from corn cob for removing brilliant green dye from water, achieving up to 99.5% removal efficiency, highlighting its potential for wastewater treatment.

Corn cob can reinforce composites with polymer or natural matrices. Fouly *et al.* (2021, 2022) showed that adding 8% to epoxy or up to 20% to polylactic acid improves strength, stiffness, and wear resistance. Husseinsyah *et al.* (2015) found enhanced tensile strength in soy protein composites, though elasticity decreased. Choi *et al.* (2022) used corn cob in thermal boards, achieving good heat storage. Zhu *et al.* (2018) reported peak properties at 40% corn cob in high density polyethylene (HDPE), with water absorption increasing at higher levels. Yeng *et al.* (2013) improved corn cob–chitosan composites using a crosslinking agent. Mohammed and Salih (2023) investigated how corn cob particle size affects the mechanical properties (hardness, impact resistance, and compressive strength) of composites made with unsaturated polyester resin. Two particle sizes (53 µm and 710 µm) and reinforcement levels (0 to 30%) were tested using manual molding. Results showed that increasing the corn cob content improved mechanical properties, regardless of particle size. Tribot *et al.* (2018) developed composite materials using corn cob powder as reinforcement and a lignosulphonate-based matrix. The study used a design of experiments to assess how fiber content, particle size, and compaction pressure affect composite strength. The optimal compressive strength was 18 MPa with a Young's modulus of 270 GPa. Particle size had the greatest impact, with rougher particles (low convexity) leading to better adhesion and higher strength. The mechanical properties such as tensile strength, compressive strength, flexural strength, Shore hardness, vibrations, water absorption, as well as SEM, Raman, and FTIR analyses for composites reinforced with crushed corn cob were also investigated in Mirițoiu *et al.* (2021), Mirițoiu and Rădoi (2024), Bolcu *et al.* (2024), Stănescu *et al.* (2024), and Mirițoiu *et al.* (2025). Additionally, the influence of dammar resin on mechanical properties in combination with crushed corn cob was also examined (see Bolcu *et al.* (2024)).

The only aspect yet to be studied was the influence of crushed corn cob on the compressive strength properties, specifically to determine the maximum mass percentage at which the material maintains acceptable strength properties, and at what mass percentage the materials no longer hold engineering relevance. Only compressive strength was considered because, according to Miriţoiu *et al.* (2025) or Stănescu *et al.* (2024), the tensile and flexural strengths are very low, making these materials suitable only as sandwich structures with natural fiber facings to enhance their strength.

This research investigated the influence of crushed corn cob reinforcement on the compressive strength of composite materials with a dammar-based matrix. The objective of the study was to fabricate composite materials reinforced with crushed corn cob, using different reinforcement ratios ranging from 50% to 67%. Compressive strength was determined by subjecting the samples to compressive loading. The results were analyzed to identify significant differences and to determine the reinforcement percentage beyond which the materials no longer hold engineering relevance. Another objective was to determine the percentage at which the strength decreases by more than 50% compared to the initial samples. The experimental conclusions were then statistically validated.

EXPERIMENTAL

Materials

Composite materials with various reinforcement percentages starting from 50% were used. The synthetic epoxy resin was sourced from a local supplier, as referenced in Polydis (2023), with its technical specifications available on the manufacturer's website (Resoltech 1050, 2023). The dammar resin was also obtained locally (Foita de Aur 2023). The crushed corn stalks were collected following the maize harvest in the Baia de Fier region (Gorj County, Romania). The fragmentation process was performed using a conventional cereal grinder available locally in Baia de Fier. The rollers of the grinding equipment were set to maintain a spacing of about 1500 to 2000 µm. A hybrid matrix was employed, consisting of a majority percentage of dammar (60%) and a minority percentage (40%) of Resoltech 1050 epoxy resin with 1058s hardener. The hybrid matrices were mixed with the reinforcement and then allowed to undergo polymerization. The procedure used is detailed below in the *Methods* section. The materials used in the present research are presented in Table 1.

The epoxy resin has a density of 1.14 g/cm³, while the hardener has a density of 0.97 g/cm³. The epoxy resin has a viscosity of 1300 MPa·s, while the hardener has a viscosity of 117 MPa·s. The epoxy resin combined with the hardener have a flexion modulus of 3500 MPa, maximum strength 82 MPa, and elongation at yield of 2.4% (Resoltech 1050, 2023). Dammar resin is reported to have a dynamic viscosity ranging from 38.36 to 41.69 MPa·s and a kinematic viscosity between 41.3 and 41.5 cSt (Kremer Pigmente 2024). Additionally, its density is between 1.04 and 1.12 g/cm³, and it has a melting point of approximately 150°C (Carl Roth 2024).

The materials were cast one at a time and then tested to determine the reinforcement percentage beyond which they no longer exhibited compressive strength. It was observed that at 67% reinforcement, the strength dropped close to zero. As a result, no further samples with 68% reinforcement were cast, since this would have led to unnecessary material consumption, and the compressive strength was unlikely to improve, given that the amount of resin would no longer be sufficient to ensure proper particle adhesion.

Methods

The initial starting material consisted of 50% crushed corn cob and 50% hybrid matrix. The reinforcement percentage was increased by 10% increments, and the reduction in tensile strength was measured. The reinforcement content was further increased incrementally until the material no longer exhibited adequate tensile strength or engineering relevance. This value is crucial for composite material manufacturers to understand how and to what extent the quantity of crushed corn cob should be adjusted depending on the material's application.

Table 1. Composite Materials

Criteria Number	Mass Fraction of the Crushed Corn Con Reinforcement (%)	Mass Fraction of the Matrix Based on Dammar Resin (%)	Material Type (Abbreviation)
1	50	50	CCC50
2	60	40	CCC60
3	61	39	CCC61
4	62	38	CCC62
5	63	37	CCC63
6	64	36	CCC64
7	65	35	CCC65
8	66	34	CCC66
9	67	33	CCC67

To obtain the proportions in Table 1, a Shimadzu TXB622L (Kyoto, Japan) balance with a precision of 0.01 g was used. For each type of material presented in Table 1, 15 specimens were cast. To illustrate the casting process, the steps for specimens with 50% reinforcement and 50% matrix were detailed. For this type of material, a total mass of 400 g was combined (approximately 200 g of reinforcement and 200 g of matrix). The exact values for each material were centralized in Table 2.

Table 2. Mass Values for Each Material

Criteria Number	Reinforcement Mass (g)	Matrix Mass (g)	Material Type (Abbreviation)
1	199.98	200.02	CCC50
2	221.05	178.95	CCC60
3	242.08	157.92	CCC61
4	261.89	138.11	CCC62
5	282.04	117.96	CCC63
6	284.17	115.83	CCC64
7	289.26	110.74	CCC65
8	292.34	107.66	CCC66
9	298.44	101.56	CCC67

Initially, the matrix with the hardener was poured until an approximate value of 200 g was reached. Then, up to the value of 400 g, the reinforcement was added. The two components were homogenized by mixing, and samples of the mixed components (resin and reinforcement) were placed into 15 cylindrical silicone molds. The cylindrical molds conformed to the ASTM D695-15 (2016) standard. The poured composition was subjected to a force of 150 daN per material. The pressure was applied to help compact de material, to ensure proper bonding between the reinforcement and matrix and remove air pockets. It was applied before gelation, and the goal was to help resin penetrate the reinforcement and ensure uniform distribution. The average mass of a specimen was approximately 21 g (± 2 g). Residual material remained in the bowl where the initial mixing was performed and was considered unrecoverable waste.

A few examples of the specimens obtained through the procedure specified above are shown in Fig. 1.

Reinforcement and matrix were introduced into a bowl, ensuring their total weight reached 400 grams, as specified in Table 2. From the 400 grams (which is the *total amount*) in the mixing bowl, 15 cylindrical samples were cast to create the test specimens. Each sample had an average mass of 21 g (± 2 g), therefore, the *total amount* of material used for the specimens was determined using Eq. 1.

$$total\ ammount\ for\ specimens = 15 \cdot 21 = 315\text{g} \tag{1}$$

The amount of material remaining in the mixing bowl was determined using Eq. 2.

$$remaining\ material = total\ ammount - total\ ammount\ for\ specimens = 85\text{g} \tag{2}$$

The *remaining material* was considered *unrecoverable waste.* The densities of the samples corresponding to the 9 different materials ranged from 447.5 to 542.3 kg/m^3.

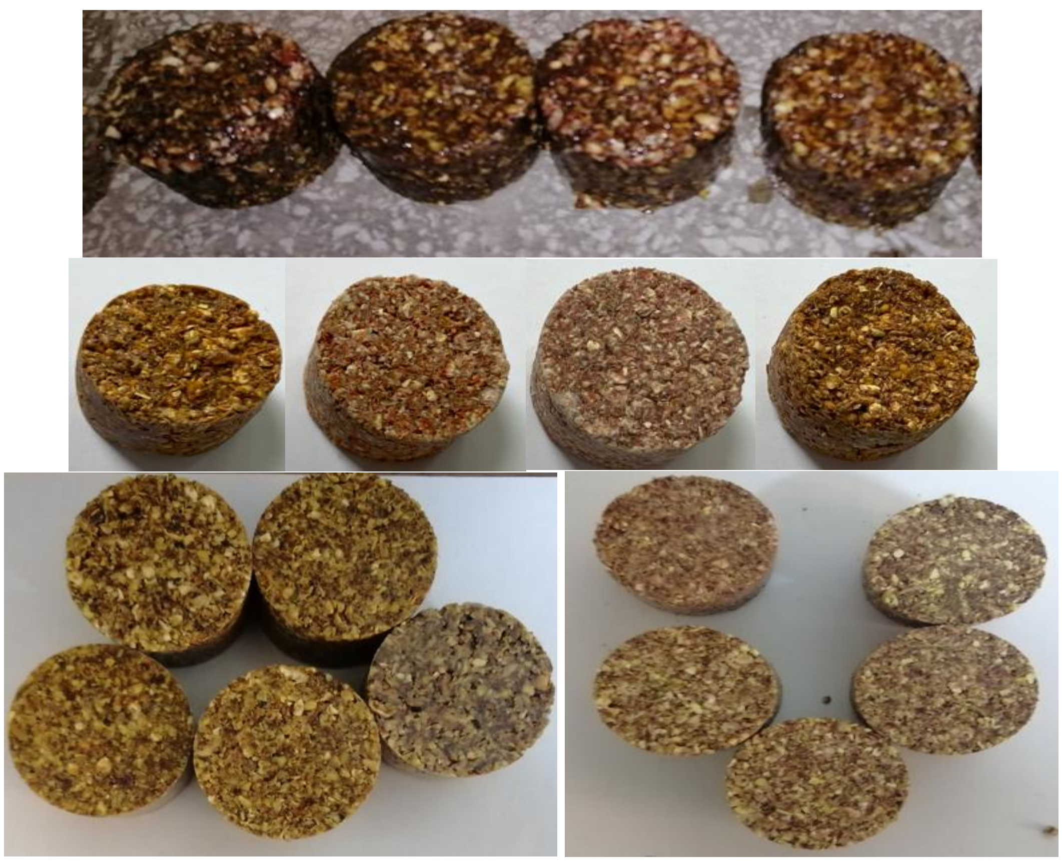

Fig. 1. Some examples with the specimens used for the tensile test

Test Standards and Characterizations

Compression test

For the compression test, 15 cylindrical samples were cast for each type of material presented in Table 2. The compression test was conducted in accordance with ASTM D695 (2016). The dimensions of the samples were in accordance with the specified standard, namely: Φ30x60 mm. A universal testing machine (LGB Testing Equipment, Azzano San Paolo, Italy) equipped with a compression testing device (compression plates) was used.

The compression test conducted in this research was static, with the force applied to one of the faces of the cylinder (along its generatrix) through the compression platen mounted on the movable crosshead of the testing machine. The other face of the cylinder was simply supported on the opposite compression platen, positioned in the bellows crosshead area of the testing machine. The force was applied slowly and continuously until the material fractured. The rate of force application was 1.5 mm/min, which falls within the range of 0.5 mm/min to 5 mm/min (0.02 inches/min to 0.2 inches/min) specified by the standard. The breaking strength was automatically provided by the testing machine’s software (LGB Easy Test). Since the influence of the reinforcement on compressive strength was studied, only the tensile strength was important (as a mechanical parameter) from the compression test. This value was provided directly by the testing machine’s software.

Statistical Interpretation of Experimental Data

As specified in the introduction paragraph of the present article, this research studied the influence of the percentage of crushed corn cob reinforcement on the compression strength. The focus was to determine the percentage of crushed corn cob at which the compression strength decreases by 50% compared to the reference samples (considered in this case as 50% matrix and 50% reinforcement). Experimental determinations continued to identify the percentage of reinforcement at which the material exhibits very low strength, thus limiting its engineering applicability. The statistical tests were made in Microsoft Excel (Microsoft Corp., Redmond, WA, USA) and G*Power (Heinrich Heine Universitat, Dusseldorf, Germany).

A preliminary test used to assess whether the results of the study in this research are valid and reliable was the power analysis test. This test refers to determining the likelihood that this research will detect a true effect under a specific set of conditions (the compression strength varies with the mass fraction of the reinforcement). The power analysis test can be used to determine the required number of samples and to assess the power of an existing study, based on both sample and effect size (Cohen 1992; Lenth 2001; Dattalo 2008; Murphy and Myors 2022). For this test, the first group, CCC50, was considered as the reference group. Then, comparisons were made between the subsequent groups and this first group considered as the reference. For each group compared to CCC50, the difference in means was determined with Eq. 3,

$$\Delta\mu = \mu_{CCC50} - \mu_{CG} \tag{3}$$

where μ_{CCC50} is the mean of the reference group and μ_{CG} is the mean of the comparison group. The pooled standard deviation was determined with Eq. 4,

$$s_{psd} = \sqrt{\frac{s_{CCC50}^2 + s_{CG}^2}{2}} \tag{4}$$

where s_{CCC50} is the standard deviation of the reference group and s_{CG} is the standard deviation of the comparison group.

The effect size d (Cohen's d) was determined with Eq. 5.

$$d = \Delta\mu \cdot s_{psd}^{-1} \quad (5)$$

To determine the effect size (small, medium, or large) of the result from Eq. 5, its absolute value was compared with the reference values (0.2; 0.5; 0.8). The statistical power was then determined with Eq. 4, where n is the sample size per group (15 for the present research).

$$t = d \cdot \left(\sqrt{\frac{2}{n}}\right)^{-1} \quad (6)$$

Based on the effect size (usually d> 0.8) and statistical power (t should be around 1) values, it can be concluded if the number of samples is sufficient to detect significant differences.

A one-way ANOVA test was conducted to determine whether the crushed corn cob has any influence over the sample's compression strength. This statistical approach is a method utilized to assess whether meaningful variations exist among the averages of three or more distinct groups. When the group averages are relatively similar, the null hypothesis is accepted as valid. If differences are observed, then the alternative hypothesis is supported, suggesting that at least one group's mean deviates from the others. In the context of this study, these principles are interpreted as follows: if the averages of the measured outcomes are equivalent, it implies that the crushed corn cob does not significantly impact the compression strength. Conversely, if the averages differ, it indicates that crushed corn cob exerts a notable effect, leading to the rejection of the null hypothesis (Ntumi 2021).

As explained by Roberts and Russo (1999), in a one-way ANOVA test, the overall mean of all observations is calculated using Eq. 7. In this formula, X_{ij} denotes the individual data points, and N represents the total number of observations across all groups:

$$\bar{X} = \frac{\sum X_{ij}}{N} \quad (7)$$

Next, the mean for each group is calculated using Eq. 8,

$$\bar{X_\iota} = \frac{\sum X_i}{n_i} \quad (8)$$

where X_i represents the values within group i, and n_i denotes the number of observations in that group.

Subsequently, the sum of squares for variations between groups and within groups was calculated using Eqs. 9 and 10.

$$SS_B = \sum n_i \cdot (\bar{X_\iota} - \bar{X})^2 \quad (9)$$

$$SS_W = \sum n_i \cdot \left(\sum X_{ij} - \sum X_i\right)^2 \quad (10)$$

The degrees of freedom for variations between groups and within groups were calculated using Eqs. 11 and 12,

$$df_B = k - 1 \quad (11)$$

$$df_W = -k + N \quad (12)$$

where k is the number of groups and N is the total number of observations.

The mean squares for variations between groups and within groups were calculated using Eqs. 13 and 14.

$$MS_B = \frac{\sum n_i \cdot (\overline{X_i} - \bar{X})^2}{k-1} \tag{13}$$

$$MS_W = \frac{\sum n_i \cdot \left(\sum X_{ij} - \sum X_i\right)^2}{-k+N} \tag{14}$$

The F-value was calculated by dividing the value from Eq. 13 by that from Eq. 14. This F-value was then compared to the critical values derived from the F-distribution, corresponding to the appropriate degrees of freedom. The comparison yields the p-value, which represents the probability of obtaining an F-value at least as large as the computed one, assuming the null hypothesis (that the group means are equal) is true.

To ensure that the assumptions made with one-way ANOVA do not lead to false positives, the data in each group must follow a normal distribution, and the groups must exhibit homogeneity of variances. To see if the data are normally distributed within each group, the Shapiro-Wilk test was performed. This test determines whether a dataset conforms to a normal distribution. A lack of normality in the data could undermine the assumptions required for conducting a one-way ANOVA (Shapiro and Wilk 1965; Zar 1999). According to Statistic Kingdom (2024), the p-value from Shapiro-Wilk can be determined with Eq. 15, where n represents the number of observations, x_i denotes individual data labels and a_i are the Shapiro-Wilk test factors, $\bar{x}$ is the arithmetic mean of the dataset under consideration, W_1 and W_2 are the critical sets of the Shapiro-Wilk test statistics, p_1 and p_2 are the probabilities that correspond to W_1 and W_2:

$$p = p_1 + \frac{\frac{\left(\sum_{i=1}^{n} a_i \cdot x_i\right)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} - W_1}{W_2 - W_1} \cdot (p_2 - p_1) \tag{15}$$

The parameters W_1, W_2, p_1, and p_2 can be found in statistical tables, an example being Real Statistics (2024). The homogeneity of variances by using Levene's test is made afterwards. According to Gastwirth *et al.* (2009) the mean of each group is calculated. Next, for each observation j, the absolute deviation from the group mean is computed using Eq. 16, where X_{ij} is the value of *j-th* observation in group i. $\overline{X_i}$ denotes the mean of group i. Eq. 16 is as follows:

$$Z_{ij} = \left|X_{ij} - \overline{X_i}\right| \tag{16}$$

If, instead of means, the medians are determined, the Eq. 16 takes the following form, where M_i is the median of group i:

$$Z_{ij} = \left|X_{ij} - M_i\right| \tag{17}$$

The deviations are then combined into a single dataset denoted as Z_{ij}. In the end, a one-way ANOVA test is conducted with Z_{ij} as the dependent variable and group membership as independent variables, obtaining Eq. 18.

$$W = (N-k) \cdot (k-1)^{-1} \cdot \frac{\sum_{i=1}^{k} n_i \cdot (\overline{Z_i} - \bar{Z})^2}{\sum_{i=1}^{k} \sum_{j=1}^{n_i} \left(-\overline{Z_i} + Z_{ij}\right)^2} \tag{18}$$

In Eq. 18 N is the total number of observations across all groups, k is the number of groups, n_i is the number of observations in group i, $\overline{Z_i}$ is the mean of Z_{ij} values from group i, and $\bar{Z}$ is the grand mean of all Z_{ij} values. The *W-statistic* value follows a *F- distribution* with *-1+k* and *N-k* degrees of freedom. Based on *F- distribution*, the p-value is obtained (which is defined as the likelihood of observing an *F-value* equal to or greater than the calculated value, assuming the null hypothesis holds true and the group means are equal). If the p value is higher than the significance level (which is usually 0.05), then the variances are homogenous, otherwise the variances are heterogenous.

In cases where the variances are not homogeneous, the result may seemingly suggest that a false positive hypothesis was adopted with one-way ANOVA. Therefore, the specialized literature recommends an additional verification (if the variances are heterogeneous) using the Welch ANOVA test (see Delacre *et al.* 2019). The following hypotheses are adopted: the null hypothesis H_0 – the means of all groups are equal, regardless of the variance differences; the alternative hypothesis H_a – at least one group mean is significantly different from the others. The sample mean $\overline{X_i}$ and variance S_i^2 are determined with Eqs. 19 and 20, where X_{ij} are the observations in group *i* and n_i is the number of observations in group *i*.

$$\overline{X_i} = \frac{\sum X_{ij}}{n_i} \tag{19}$$

$$S_i^2 = \frac{\sum\left(X_{ij}-\overline{X_i}\right)^2}{n_i-1} \tag{20}$$

The, the weighted mean of all groups $\overline{X_W}$ is determined with Eq. 21.

$$\overline{X_W} = \left(\sum \frac{\overline{X_i}}{S_i^2}\right) \cdot \left(\sum S_i^{-2}\right)^{-1} \tag{21}$$

For k groups, the F-Welch statistics F_W is determined with Eq. 22.

$$F_W = \frac{\sum \frac{n_i\left(\overline{X_i}-\overline{X_W}\right)^2}{S_i^2}}{-1+k} \tag{22}$$

The denominator variance D_V is determined with Eq. 23.

$$D_V = \sum \left(\frac{n_i-1}{n_i}\right) \cdot S_i^{-4} \tag{23}$$

The degrees of freedom for unequal variances are determined with Eqs. 24 and 25.

$$df_1 = -1 + k \tag{24}$$

$$df_2 = \frac{\left(\sum \frac{1}{S_i^2}\right)^2}{\sum\left(\frac{n_i-1}{n_i}\right) \cdot S_i^{-4}} \tag{25}$$

The critical F-value ($F_{\propto,df_1,df_2}$) is determined by using the F-distribution at the desired significance level (usually it is considered 0.05). If the value from Eq. 22 is higher than the $F_{\propto,df_1,df_2}$ value, then the null hypothesis is rejected. This means there are significant differences between group means.

If the experimental data do not meet the normal distribution assumption when tested with the Shapiro-Wilk test, the specialized literature also recommends using the Kolmogorov-Smirnov (K-S) test as an alternative solution. Similar to other tests, two hypotheses are adopted: the null hypothesis H_0 - the data follows a specified distribution and the alternative hypothesis H_a - the data does not follow the specified distribution (Massey 1951; Lilliefors 1967; Fasano and Franceschini 1987; Dimitrova *et al.* 2020). In this test, the empirical cumulative distribution function is determined with Eq. 26, where x_0 is the number of values, x is a value in the dataset and n is the total number of samples.

$$f_n(x) = \frac{x_0 \leq x}{n} \tag{26}$$

The theoretical cumulative distribution function was determined with Eq. 27, where Φ is the normal cumulative distribution function, μ is the sample mean and $\bar{\sigma}$ is the standard deviation.

$$f(x) = \Phi \cdot \left(\frac{x-\mu}{\bar{\sigma}}\right) \tag{27}$$

The Kolmogorov-Smirnov test statistic D is the maximum absolute difference between the empirical cumulative distribution function. The critical value D_α is chosen based on the sample size and the significance level. If D> D_α then the null hypothesis is rejected, otherwise is fulfilled. The statistical p-value cand be determined with Eq. 28, where Q is a function dependent on the asymptotic distribution of the test statistic.

$$\mathrm{p} = Q \cdot (D \cdot n^{0,5}) \tag{28}$$

If p> α (where α is the significance level which may be 0.01, 0.05 or 0.1), then the null hypothesis is fulfilled, otherwise is rejected.

The last statistical test performed in the analysis was a Post hoc ANOVA with Bonferroni correction. This method is designed to pinpoint which specific pairs of groups exhibit statistically significant differences after the initial ANOVA test has identified the existence of significant variation among groups. The Bonferroni correction is a critical step to mitigate the risk of Type I errors (false positives) that can arise when conducting multiple comparisons. By adjusting the significance level, this approach ensures that the overall error rate remains controlled. Post hoc tests play an essential role because the ANOVA test alone determines whether differences exist among groups but does not identify which groups differ from one another (VanderWeele and Mathur 2019). In the Bonferroni-adjusted post hoc analysis, the same formulas are utilized as in the standard one-way ANOVA; however, the key difference lies in the adjusted significance level. Specifically, the original significance threshold (e.g., α= 0.05) is divided by the number of pairwise comparisons conducted among the groups. This adjustment effectively reduces the chance of false positives while maintaining the integrity of the statistical analysis. This method is particularly useful when analyzing datasets with multiple groups, as it provides a robust mechanism for isolating meaningful differences.

RESULTS AND DISCUSSION

Compression Test

For each type of material listed in Table 1, 15 different specimens were cast and tested. The duration of the curing period was 8 days/ material. For each of the 9 different types of materials, the matrix type was kept constant (with the formula: 60% dammar resin and 40% Resoltech 1050 epoxy resin with Resoltech 1058s hardener), while the mass fraction of the reinforcement was varied as follows: 50%, 60%, and then incrementally by 1% up to 67%. This approach was used to determine at what percentage the strength decreases by 50% compared to the reference samples. Additionally, another goal was to determine the mass percentage of crushed corn cob at which the materials no longer exhibit significance from an engineering applications perspective. This is considered achieved when the compression strength reaches a very low value, thereby limiting the practical applicability of the materials. The reference samples were defined as those containing 50% matrix and 50% reinforcement. The reinforcement percentage was increased because the main idea of the research was to use as much agricultural waste material as possible (such as corn cob in this case).

For each of the 9 types of materials used, a centralized figure will be presented (Fig. 2), displaying a characteristic force (kN) - traverse stroke (mm) curve. The characteristic curves selected are those whose values were closest to the arithmetic mean obtained from the experimental data following the testing of 15 specimens.

The arithmetic means of the mechanical properties (force, strength, and traverse stroke) obtained from the compression tests are centralized in Table 3.

Table 3. Arithmetic Means of the Mechanical Properties Obtained from the Compression Tests

Sample	F_{max} (kN)	R_m (MPa)	Traverse Stroke (mm)
CCC50	28.17	22.44	15.28
CCC60	21.4	17.1	15.08
CCC61	20.3	16.2	12.8
CCC62	19.38	15.44	10.02
CCC63	12.2	9.75	9.8
CCC64	9.15	7.28	7.5
CCC65	6.4	5.14	6.9
CCC66	3.25	2.6	5.42
CCC67	0.42	0.34	1.96

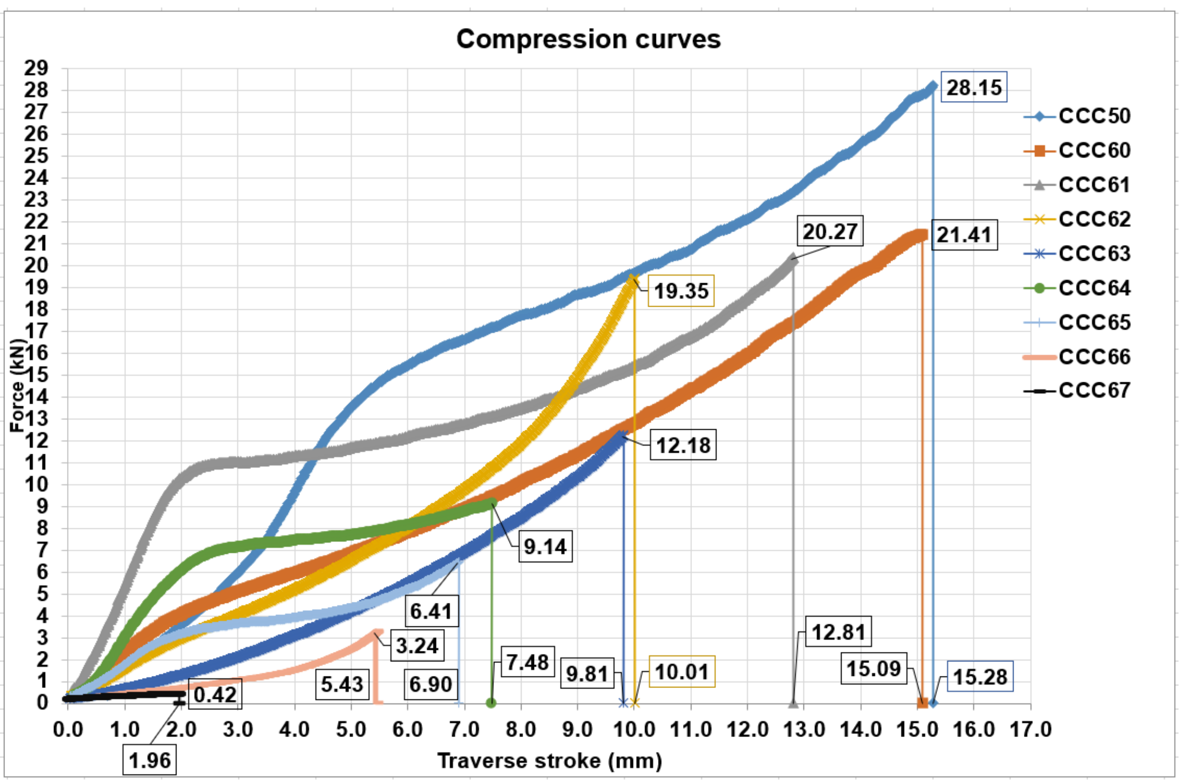

Fig. 2. Force-traverse stroke curves for samples with values closest to the arithmetic mean

For a percentage of 63% crushed corn cob, the breaking strength decreased by more than 50% compared to the chosen reference value (CCC50, where a composition of 50% matrix and 50% reinforcement was used). At a percentage of 67% crushed corn cob, the material practically no longer exhibited mechanical strength. This can be explained by the fact that 1 g of resin occupied a much smaller volume compared to 1 g of reinforcement (crushed corn cob). As a result, there was insufficient resin in the material to ensure adhesion between the reinforcement particles. The reinforcement particles were left without bonding resin, leading to the formation of micro voids in the material and the displacement of particles relative to one another. This naturally resulted in the formation of cracks during testing and a significant weakening of the material's strength.

In Fig. 3, all the experimental values of tensile strength corresponding to the 15 specimens manufactured from the 9 different types of materials are presented. These values were further used in statistical tests to study the influence of the reinforcement on the strength of the materials. A preliminary analysis of the results revealed that the tensile strength decreased as the percentage of crushed corn cob increased. This can be explained by the fact that crushed corn cob particles have sharp, irregular edges, which, once introduced into the matrix, contribute to the development of internal mechanical stresses. These stresses, when subjected to a certain load, lead to the formation of microcracks, which over time grow and propagate into macrocracks, ultimately resulting in the fracture of the specimen. Therefore, as the percentage of crushed corn cob increases, the number of sharp edges in the specimen also increases, thereby reducing the tensile strength based on the considerations outlined above.

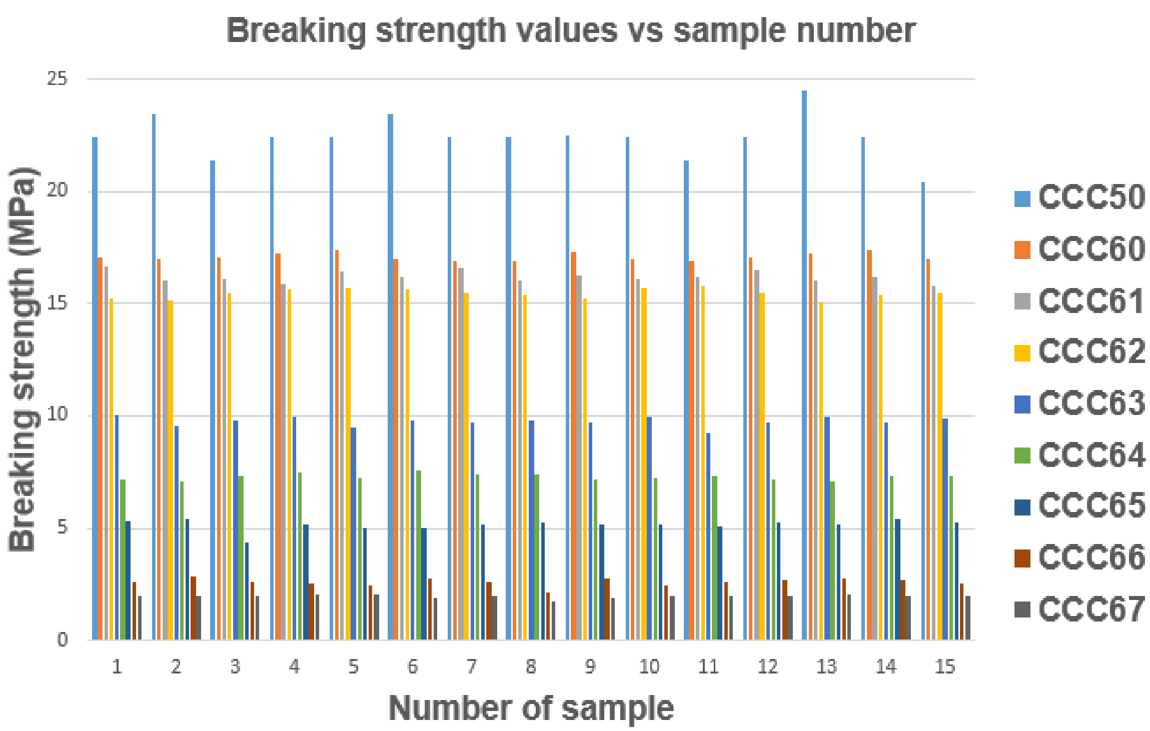

Fig. 3. Compression strength values for the 15 types of samples

The first statistical test conducted was the power analysis test, as shown in Table 4. The notations in Table 4 are related to those mentioned in the section Statistical Interpretation of Experimental Data in this way: μ_{CCC50} is the mean of the reference group,

μ_{CG} is the mean of the comparison group group, s_{CG} is the standard deviation of the comparison group, s_{CCC50} is the standard deviation of the reference group, s_{psd} is the pooled standard deviation, d is the effect size, and t is the statistical power.

Table 4. Power Analysis Test Results

Group	μ_{CCC50}	μ_{CG}	S_{CCC50}	s_{CG}	s_{psd}	d	t	Sample Size
CCC60	22.44	17.1	0.941	0.169	0.676	7.896	1	15
CCC61	22.44	16.2	0.941	0.259	0.690	9.038	1	15
CCC62	22.44	15.441	0.941	0.213	0.682	10.253	1	15
CCC63	22.44	9.749	0.941	0.203	0.681	18.634	1	15
CCC64	22.44	7.275	0.941	0.146	0.673	22.512	1	15
CCC65	22.44	5.135	0.941	0.242	0.687	25.174	1	15
CCC66	22.44	2.602	0.941	0.173	0.676	29.309	1	15
CCC67	22.44	1.96	0.941	0.075	0.667	30.669	1	15

To avoid limiting the present calculation to CCC50 as the reference group, combinations of the other groups were used for the statistical calculation of the power analysis test. All the results are summarized in Table 5.

In Table 5, the next parameters were marked: μ_{RG} is the reference group mean, μ_{CG} is the comparison group mean, s_{CG} is the standard deviation of the comparison group, s_{RG} is the standard deviation of the reference group, s_{psd} is the pooled standard deviation, d is the effect size and t is the statistical power.

From the analysis of Tables 4 and 5, it can be observed that the effect size $d>0.8$ and the statistical power t was approximately equal to one. Therefore, it can be concluded that the 15 samples used in the present study are sufficient to detect significant differences. The analysis strongly supports the conclusion that compressive strength varies significantly across the groups, and the sample size of 15 is more than sufficient for the observed differences.

The next statistical test is a one-way ANOVA. The following hypotheses are adopted: the null hypothesis H_0– the mass fraction of the reinforcement (crushed corn cob) has no significant influence on the compression strength; the alternative hypothesis H_a – the mass fraction of the reinforcement (crushed corn cob) has a significant influence on the compressive strength. This test is applied to all experimental data corresponding to the materials in Table 1. The results have been summarized in Table 6.

The next step is to verify the homogeneity of variances. For this purpose, the Levene's test is applied. The following hypotheses are adopted: the null hypothesis H_0 - the variances are homogeneous (p-value>0.05) and the alternative hypothesis H_a) - the variances are heterogeneous (p-value<0.05). The data are summarized in Table 7.

Table 7 reveals that the variances were not homogeneous, and thus, the hypothesis adopted with one-way ANOVA appears to be a false positive. However, in this case, the specialized literature also recommends using another statistical algorithm, namely Welch ANOVA (see Delacre *et al.* 2019). This test does not assume equal variances. The data have been summarized in Table 8. Two hypotheses were adopted: the null hypothesis H_0– there are significant differences between the group means (the mass fraction of crushed corn cob has a significant influence on compression strength); the alternative hypothesis H_a– there are no significant differences between the group means.

Table 5. Power Analysis Test Results for All Possible Combinations

Reference Group	Comparison Group	μ_{RG}	μ_{CG}	s_{RG}	s_{CG}	s_{psd}	d	t	Sample Size
CCC60	CCC61	17.1	16.2	0.169	0.259	0.218	4.114	1	15
CCC60	CCC62	17.1	15.441	0.169	0.213	0.192	8.608	1	15
CCC60	CCC63	17.1	9.749	0.169	0.203	0.187	39.293	1	15
CCC60	CCC64	17.1	7.275	0.169	0.146	0.158	62.173	1	15
CCC60	CCC65	17.1	5.135	0.169	0.242	0.209	57.235	1	15
CCC60	CCC66	17.1	2.602	0.169	0.173	0.171	84.699	1	15
CCC60	CCC67	17.1	1.96	0.169	0.075	0.130	115.70	1	15
CCC61	CCC60	16.2	17.1	0.259	0.169	0.218	-4.114	1	15
CCC61	CCC62	16.2	15.441	0.259	0.213	0.237	3.194	1	15
CCC61	CCC63	16.2	9.7493	0.259	0.203	0.232	27.687	1	15
CCC61	CCC64	16.2	7.2753	0.259	0.146	0.210	42.423	1	15
CCC61	CCC65	16.2	5.1353	0.259	0.242	0.250	44.088	1	15
CCC61	CCC66	16.2	2.6026	0.259	0.173	0.220	61.690	1	15
CCC61	CCC67	16.2	1.96	0.259	0.075	0.190	74.630	1	15
CCC62	CCC60	15.441	17.1	0.213	0.169	0.192	-8.608	1	15
CCC62	CCC61	15.441	16.2	0.213	0.259	0.237	-3.194	1	15
CCC62	CCC63	15.441	9.749	0.213	0.203	0.208	27.274	1	15
CCC62	CCC64	15.441	7.275	0.213	0.146	0.183	44.597	1	15
CCC62	CCC65	15.441	5.135	0.213	0.242	0.228	45.084	1	15
CCC62	CCC66	15.441	2.602	0.213	0.173	0.194	65.989	1	15
CCC62	CCC67	15.441	1.96	0.213	0.075	0.160	84.130	1	15
CCC63	CCC60	9.749	17.1	0.203	0.169	0.187	-39.293	1	15
CCC63	CCC61	9.749	16.2	0.203	0.259	0.232	-27.687	1	15
CCC63	CCC62	9.749	15.441	0.203	0.213	0.208	-27.274	1	15
CCC63	CCC64	9.749	7.275	0.203	0.146	0.177	13.962	1	15
CCC63	CCC65	9.749	5.135	0.203	0.242	0.223	20.608	1	15
CCC63	CCC66	9.749	2.602	0.203	0.173	0.189	37.813	1	15
CCC63	CCC67	9.749	1.96	0.203	0.075	0.153	50.762	1	15
CCC64	CCC60	7.275	17.1	0.146	0.169	0.158	-62.173	1	15
CCC64	CCC61	7.275	16.2	0.146	0.259	0.210	-42.423	1	15
CCC64	CCC62	7.275	15.441	0.146	0.213	0.183	-44.597	1	15
CCC64	CCC63	7.275	9.749	0.146	0.203	0.177	-13.962	1	15
CCC64	CCC65	7.275	5.135	0.146	0.242	0.200	10.686	1	15

CCC64	CCC66	7.275	2.602	0.146	0.173	0.160	29.149	1	15
CCC64	CCC67	7.275	1.96	0.146	0.075	0.116	45.712	1	15
CCC65	CCC60	5.135	17.1	0.242	0.169	0.209	-57.235	1	15
CCC65	CCC61	5.135	16.2	0.242	0.259	0.250	-44.088	1	15
CCC65	CCC62	5.135	15.441	0.242	0.213	0.228	-45.084	1	15
CCC65	CCC63	5.135	9.749	0.242	0.203	0.223	-20.608	1	15
CCC65	CCC64	5.135	7.275	0.242	0.146	0.200	-10.686	1	15
CCC65	CCC66	5.135	2.602	0.242	0.173	0.210	12.016	1	15
CCC65	CCC67	5.135	1.96	0.242	0.075	0.179	17.681	1	15
CCC66	CCC60	2.602	17.1	0.173	0.169	0.171	-84.699	1	15
CCC66	CCC61	2.602	16.2	0.173	0.259	0.220	-61.690	1	15
CCC66	CCC62	2.602	15.441	0.173	0.213	0.194	-65.989	1	15
CCC66	CCC63	2.602	9.749	0.173	0.203	0.189	-37.813	1	15
CCC66	CCC64	2.602	7.275	0.173	0.146	0.160	-29.15	1	15
CCC66	CCC65	2.602	5.135	0.173	0.242	0.210	-12.016	1	15
CCC66	CCC67	2.602	1.96	0.173	0.075	0.133	4.8107	1	15
CCC67	CCC60	1.96	17.1	0.075	0.169	0.130	-115.70	1	15
CCC67	CCC61	1.96	16.2	0.075	0.259	0.190	-74.630	1	15
CCC67	CCC62	1.96	15.441	0.075	0.213	0.160	-84.130	1	15
CCC67	CCC63	1.96	9.749	0.075	0.203	0.153	-50.762	1	15
CCC67	CCC64	1.96	7.275	0.075	0.146	0.116	-45.712	1	15
CCC67	CCC65	1.96	5.135	0.075	0.242	0.179	-17.682	1	15
CCC67	CCC66	1.96	2.602	0.075	0.173	0.133	-4.8107	1	15

Table 6. One-way ANOVA Test Results

F-value	p-value	Significance level
5935.96	$1.92 \cdot 10^{-158}$	0.05
Conclusion: the null hypothesis **is rejected**. The mass fraction of the reinforcement (crushed corn cob) has a significant influence on the compression strength.		

Table 7. Levene's Test Results

Levene statistic	p-value	Significance level
4.04	0.00027	0.05
Conclusion: the null hypothesis **is rejected**. The variances are heterogeneous.		

Table 8. Welch ANOVA Test Results

F_w	df_1	df_2	Significance level	$F_{\propto,df_1,df_2}$
$2.1 \cdot 10^9$	8	24.59	0.05	2.49
Conclusion: there were significant differences between the group means ($F_w > F_{\propto,df_1,df_2}$), the mass fraction of crushed corn cob has a significant influence on compression strength. The alternative hypothesis **is rejected**.				

The next step in validating the hypothesis from the one-way ANOVA test that the mass fraction of crushed corn cob influences the compressive strength value in the study to verify that the data in each group follows a normal distribution. For this purpose, the Shapiro-Wilk test was applied to all raw experimental data. Similarly, two hypotheses were adopted: the null hypothesis H_0 - the data has a normal distribution ($p > \alpha$), and the alternative hypothesis - the data does not have a normal distribution ($p < \alpha$). All the statistical results are written in Table 9.

Mathematical statistics allows the selection of a significance level α between the values 0.1, 0.05, and 0.01. From the analysis of Table 9, it was observed that for a significance level of 0.01, all p-value results were higher (resulting that for the materials CCC50, CCC60, CCC61, CCC62, CCC63, CCC64, CCC66, and CCC67, the experimental data followed a normal distribution, and the null hypothesis was satisfied), except for the material CCC65, for which the null hypothesis was rejected (*i.e.*, the experimental data does not follow a normal distribution).

Table 9. Shapiro-Wilk Test Results

Material	p-value
CCC50	0.034
CCC60	0.098
CCC61	0.643
CCC62	0.341
CCC63	0.116
CCC64	0.928
CCC65	0.001
CCC66	0.259
CCC67	0.017

Because the null hypothesis of the Shapiro-Wilk test was not satisfied for all the materials considered, the Kolmogorov-Smirnov test for normality was applied. The same two hypotheses were adopted: the null hypothesis H_0 - the experimental data follows a normal distribution, and the alternative hypothesis H_a - the experimental data does not follow a normal distribution. A significance level of 0.05 was chosen. The p-value results obtained from applying the Kolmogorov-Smirnov test are summarized in Table 10.

Table 10. Kolmogorov-Smirnov Test Results

Material	CCC50	CCC60	CCC61	CCC62	CCC63	CCC64	CCC65	CCC66	CCC67
p-value	0.117	0.588	0.739	0.802	0.431	0.818	0.378	0.778	0.107

The p-values were higher than the significance level (0.05), so the null hypothesis was satisfied, and the experimental data followed a normal distribution according to Kolmogorov-Smirnov test.

Table 11. *Post hoc* ANOVA with Bonferroni Correction Test Results

Comparison	F-statistic	p-value (Bonferroni Corrected)	$\overline{X_{gr1}}$	$\overline{X_{gr2}}$	MS_B	MS_W
CCC50 vs CCC60	467.6149	$1.87 \cdot 10^{-17}$	22.44	17.1	213.867	0.457
CCC50 vs CCC61	612.6851	$5.09 \cdot 10^{-19}$	22.44	16.2	292.032	0.476
CCC50 vs CCC62	788.4728	$1.70 \cdot 10^{-20}$	22.44	15.441	367.36	0.465
CCC50 vs CCC63	2604.452	$1.28 \cdot 10^{-27}$	22.44	9.749	1207.898	0.463
CCC50 vs CCC64	3801.057	$6.75 \cdot 10^{-30}$	22.44	7.275	1724.753	0.453
CCC50 vs CCC65	4753.352	$3.01 \cdot 10^{-31}$	22.44	5.135	2245.886	0.472
CCC50 vs CCC66	6442.949	$4.35 \cdot 10^{-33}$	22.44	2.602	2951.398	0.458
CCC50 vs CCC67	7054.671	$1.23 \cdot 10^{-33}$	22.44	1.96	3145.728	0.445
CCC60 vs CCC61	126.9403	$2.34 \cdot 10^{-10}$	17.1	16.2	6.075	0.047
CCC60 vs CCC62	555.7537	$1.88 \cdot 10^{-18}$	17.1	15.441	20.633	0.037
CCC60 vs CCC63	11579.61	$1.22 \cdot 10^{-36}$	17.1	9.749	405.242	0.034
CCC60 vs CCC64	28991.46	$3.26 \cdot 10^{-42}$	17.1	7.275	723.930	0.024
CCC60 vs CCC65	24569.17	$3.30 \cdot 10^{-41}$	17.1	5.135	1073.649	0.043
CCC60 vs CCC66	53805.46	$5.71 \cdot 10^{-46}$	17.1	2.602	1576.295	0.029
CCC60 vs CCC67	100409.1	$9.22 \cdot 10^{-50}$	17.1	1.96	1719.147	0.017
CCC61 vs CCC62	76.52115	$6.09 \cdot 10^{-8}$	16.2	15.441	4.316	0.056
CCC61 vs CCC63	5749.305	$2.13 \cdot 10^{-32}$	16.2	9.749	312.083	0.054
CCC61 vs CCC64	13498.06	$1.43 \cdot 10^{-37}$	16.2	7.275	597.372	0.044
CCC61 vs CCC65	14578.15	$4.87 \cdot 10^{-38}$	16.2	5.135	918.201	0.062
CCC61 vs CCC66	28542.64	$4.06 \cdot 10^{-42}$	16.2	2.602	1386.656	0.048
CCC61 vs CCC67	41772.9	$1.97 \cdot 10^{-44}$	16.2	1.96	1520.832	0.036
CCC62 vs CCC63	5579.293	$3.23 \cdot 10^{-32}$	15.441	9.749	242.991	0.043
CCC62 vs CCC64	14917.28	$3.53 \cdot 10^{-38}$	15.441	7.275	500.126	0.033
CCC62 vs CCC65	15244.45	$2.61 \cdot 10^{-38}$	15.441	5.135	796.602	0.052
CCC62 vs CCC66	32659.38	$6.16 \cdot 10^{-43}$	15.441	2.602	1236.235	0.037
CCC62 vs CCC67	53085.05	$6.89 \cdot 10^{-46}$	15.441	1.96	1363.098	0.025
CCC63 vs CCC64	1462.167	$3.71 \cdot 10^{-24}$	9.749	7.275	45.905	0.031
CCC63 vs CCC65	3185.462	$7.86 \cdot 10^{-29}$	9.749	5.135	159.667	0.050
CCC63 vs CCC66	10723.72	$3.55 \cdot 10^{-36}$	9.749	2.602	383.061	0.035
CCC63 vs CCC67	19325.97	$9.47 \cdot 10^{-40}$	9.749	1.96	455.052	0.023
CCC64 vs CCC65	856.5744	$5.54 \cdot 10^{-21}$	7.275	5.135	34.347	0.040
CCC64 vs CCC66	6372.916	$5.06 \cdot 10^{-33}$	7.275	2.602	163.753	0.025
CCC64 vs CCC67	15672.21	$1.77 \cdot 10^{-38}$	7.275	1.96	211.895	0.013
CCC65 vs CCC66	1082.933	$2.27 \cdot 10^{-22}$	5.135	2.602	48.108	0.044
CCC65 vs CCC67	2344.893	$5.49 \cdot 10^{-27}$	5.135	1.96	75.620	0.032
CCC66 vs CCC67	173.575	$5.74 \cdot 10^{-12}$	2.602	1.96	3.097	0.017

The final statistical test performed was the *Post hoc* ANOVA test with Bonferroni correction. This test compares the experimental data groups pair by pair and indicates whether there are significant differences between the experimentally determined values of compressive strength. The same two hypotheses were adopted: the null hypothesis H_0 (p-value > α)- the crushed corn cob does not have a significant effect on compression strength, and the alternative hypothesis H_a (p-value < α)- the crushed corn cob has a significant effect on compression strength. A significance level of 0.00138 was chosen (the initial significance of 0.05 level is divided to 36 comparisons). All the results from ANOVA post-hoc test with Bonferroni correction are written in Table 11.

In Table 11, the p-value was much smaller than the significance level α (which is chosen to be 0.00138), indicating that the alternative hypothesis is adopted: crushed corn cob has a significant effect on the compressive strength value. In Table 11, the next parameters were marked: MS_B and MS_W are the mean squares between and within groups, $\overline{X_{gr1}}$ and , $\overline{X_{gr2}}$ are means for group 1 and group 2 from the comparisons

The mass fraction of the reinforcement had a significant influence on the breaking strength, causing it to decrease as the percentage increases. This result can be phenomenologically explained by the fact that crushed corn cob particles have sharp and irregular edges. Once embedded in the matrix, they contribute to the appearance of stress concentrators within the material. These stress concentrators, under mechanical loading (compression in this case), lead to the formation of microcracks which, as the applied force increases, develop into macrocracks that propagate within the body until its ultimate failure.

CONCLUSIONS

1. The null hypothesis was adopted, stating that the mass fraction of the reinforcement (crushed corn cob) has no significant influence on the compression strength, and this hypothesis was rejected through the one-way ANOVA test. Additionally, to ensure that the one-way ANOVA test does not introduce false positive errors, normal distribution tests of the data and homogeneity of variance tests were performed.
2. From a statistical perspective, it was determined that crushed corn cob influences the compressive breaking strength (the null hypothesis was rejected in both the one-way ANOVA test and the post hoc ANOVA with Bonferroni correction).
3. The incorporation of crushed corn cob into the structure of the composite material led to a decrease in compressive strength. This can be explained by the fact that crushed corn cob particles have sharp edges and irregular surfaces, which, when embedded in the matrix, create stress concentrators. During loading, these stress concentrators produce microcracks at low stress levels, which eventually develop into macrocracks that propagate rapidly, ultimately leading to the material's failure.
4. Since lightweight concrete with less dense aggregates (such as expanded polystyrene, perlite, or expanded clay) has a compressive strength in the range 10 to 15 MPa, it can be replaced by the CCC50 to CCC62 material set, as they have higher compression strengths. The materials CCC50 to CCC62 have also reduced carbon footprint (because both crushed corn cob and dammar resin are natural materials) compared to lightweight concrete with less dense aggregates.

5. A future experiment that could be considered is studying the effect of crushed corn cob particle size on compressive tensile strength. It would be expected that if the particle size is reduced, the mechanical properties would improve, as sharp edges would be minimized and stress concentrators would be reduced. Additionally, ideally, a solution would be found for grinding the corn cob in such a way that the particles have as many rounded surfaces as possible.

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