The Mechanical Performance of Eggshell and Date Seed Powder Eco-Friendly Composite Materials

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ABSTRACT

This study aims to improve the mechanical performance of environmentally friendly composite materials using Eggshell Powder (ESP) and Date Seed Powder (DSP) as reinforcement materials in epoxy resin. The samples were prepared with different weight ratios (35%, 45%, and 55%) and different particle sizes (ESP: 220 and 425 μm; DSP: 850 and 1150 μm), and tested according to the international standards for the evaluation of hardness, tensile strength, flexural, and impact resistance. The findings revealed that increasing the weight fraction led to a significant improvement in the mechanical properties, with the DSP sample recording 850 μm at 55%, the highest tensile strength (67.3 MPa) and hardness (100.3 HV), due to the homogeneous distribution of particles and their strong bonding with the base material. The results also exhibited that the smaller particles (ESP 220 μm) outperformed hardness (115.3 HV), while the larger particles (DSP 1150 μm) excelled in impact resistance (16.9 J/cm^2) for their ability to absorb energy. The DSP 850 μm sample scored superior values in most tests, making it ideal for structural applications requiring high durability. The study confirms that DSP and ESP-enhanced composite materials are a promising alternative to conventional materials, with a balance between sustainability and mechanical performance. DSP 850 μm with 55% is proposed for high-demand applications, and DSP 1150 μm for those requiring shock resistance.

Keywords-environmentally friendly composite materials; eggshell; date seed; weight fraction; particle size; mechanical properties

I. INTRODUCTION

Eggshell Powder (ESP) and Date Seed Powder (DSP) are sustainable alternatives to conventional fillers in composite materials. ESP, composed of approximately 94% calcium carbonate ($CaCO_3$), offers high calcium content and acts as a reinforcing agent in polymer and cementitious matrices [1]. Similarly, date seeds—a byproduct of date fruit processing—contain lignocellulosic fibers and organic compounds, providing potential for lightweight, biodegradable composites [2].

Investigations into the epoxy resin composites reinforced with ESP demonstrate promising mechanical enhancements. The experimental results showed that eggshell-modified epoxy composites exhibited superior mechanical performance compared to the unmodified resin ones. It has been shown that epoxy composites containing eggshell exhibited Young's modulus increases of 18%, tensile strength improvements of 50%, and deformation increases of 35% compared to the unreinforced epoxy [3]. Studies on polyamide and nylon black composites reinforced with ESP demonstrate progressive mechanical property improvements with an increasing filler content. In particular, tensile strength investigations revealed that nylon black composites with ESP exhibited gradual strength increases corresponding to higher ESP percentages. The optimal formulation containing 75% nylon black and 25% ESP (designated as NB5) produced tensile strength values 58.16% higher than the comparable polyamide-based composites with the same ESP content [4]. Similar trends were observed for the flexural properties, where NB5 composites demonstrated a flexural strength 47.91% higher than the polyamide composites with an equivalent ESP content. The enhanced performance was attributed to an improved fiber-matrix bonding resulting from surface modification of the reinforcing materials [4]. Beyond polymer applications, ESP has shown promise as a cement replacement material. When incorporated into Portland limestone cement (CEM II 42.5R), ESP acts primarily as a filler rather than a pozzolanic material due to its high calcium content. The incorporation of ESP influences the setting times, generally producing an acceleration effect on cement hydration compared to the control samples [5]. ESP improves the compressive strength in cementitious materials at low replacement levels (5%-10%), but excessive substitution (>15%) weakens the structural integrity [6].

Date Palm Seed Pod Ash (DPSA) represents another promising agricultural waste stream with potential applications in composite materials. Chemical analysis using X-ray fluorescence spectrometry reveals that DPSA contains a high silica content (42.75 wt%), with a total SiO_2+Al_2O_3+Fe_2O_3 content of 45.38 wt% [5]. While this composition falls below the 70% threshold typically associated with good pozzolanic materials, DPSA still demonstrates beneficial properties when incorporated into the composite systems. Seed powders exhibit moderate tensile and impact strength in epoxy composites, with optimal performance at 30%-40% filler content. Higher loads lead to agglomeration and reduced ductility [2]. Authors in [7] reviewed the use of date palm ash and ESP as alternative cement materials in concrete mixes. The experiments showed that the optimal mixture of 20% palm ash and 2% egg shell powder achieved a compressive resistance of 57.53 MPa with a reduction in the water absorption by 22.96%, while a life cycle analysis demonstrated a reduction in global warming of up to 15.46%, confirming the feasibility of the laboratory and environmental solution [7]. Authors in [8] synthesized environmentally friendly compounds using ESP and marble powder with weight ratios of up to 60% through open molding. The results showed that increasing the marble increases density and hardness, while the eggshell ratio increases the tensile strength. The best performance was provided by the pure marble compounds according to the analysis of MADAM-TOPSIS [8]. Authors in [9] studied the effect of adding Date Palm Ash (DPA) and ESP as alternative cement materials in concrete mixtures in varying proportions. Tests showed that the optimal mixture of 20% DPA and 2% ESP achieves a compressive strength of about 57.5 MPa and reduces the water absorption by about 23%. It also recorded a significant reduction in the CO_2 emissions thanks to the reduction in the use of traditional cement, underscoring the sustainable environmental aspects of this technology. Authors in [10] examined the environmental and mechanical performance of eco-friendly concrete by partially replacing cement with DPA at 10%–40% and ESP at 1%–4%. The optimal mixture (20% DPA and 2% ESP) showed a compressive strength of 57.53 MPa, with a water absorption reduction of 22.96%. The life cycle analysis according to ISO 14040 and ReCiPe revealed a reduction in the emissions of up to 15.46%, with the best environmental efficiency documented for the 40% DPA blend. Authors in [11] reviewed the development of bamboo and epoxy fiber compounds injected with ESP (2%-6% by weight) as biological waste. The best performance was recorded at 4% filler with an increase in the tensile strength of 13.5% and elasticity of 16.4% compared to the base mix. The SEM analyses exhibited a homogeneous distribution of molecules and enhanced bonding between the fibers and the matrix. The study also confirms the feasibility of using egg shells as waste to produce light and sustainable compounds. Authors in [12] examined the use of ESP in the amount of 0%-50% by weight as a filler in environmental epoxy compounds, with an evaluation of its physical properties (density, voids, thermal behavior), mechanical properties, and friction. The results showed that the addition of 30% ESP improved the durability, while the percentage of wear and coefficient of friction increased at 50% under a load of 30 N. This modification makes it possible to produce low-cost, high-durability materials for indoor and outdoor applications [12]. Authors in [13] presented a sustainable hybrid polyester complex that combines jack and jute tree fibers with ESP filler, with a focus on the environmental use rather than on the synthetic materials. Physical and mechanical tests (tensile strength, impact resistance, hardness, and water absorption) showed significant improvements, and the FTIR and SEM analysis revealed molecular interaction and improved microstructure of these mixtures [13].

One of the most important research gaps is the scarcity of studies and research on the mechanical behavior and performance of ESP and DSP composites. In this study, the mechanical behavior of natural composite material consisting of epoxy, ESP, and DSP has been studied, with two sizes of ESP and DSP powder particles obtained (220μm and 425μm for ESP, 850μm and 1180μm for DSP) with (35%,45%, and 55 %) weight fractions for each particle size.

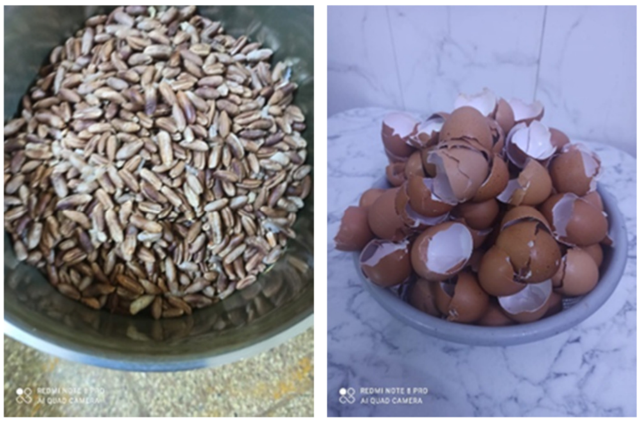
II. MATERIALS AND METHODS

A. Materials and Tools

- The base material was selected from a local resin named LP (Sikadur-52), and its properties are presented in Table I.

TABLE I. LP (SIKADUR-52) PROPERTIES

Density (g/cm³)	Tensile modulus (GPa)	Tensile strength (MPa)	Flexural strength (MPa)
1.4	2.41	24-90	34-200



(a) (b)

Fig. 1. Reinforcing materials: (a) date seeds, (b) eggshells.

Two reinforcement materials were used in this study: eggshells and DSP, as illustrated in Figure 1. A high-speed grinder was employed to produce the powder form of each reinforcement, as shown in Figure 2. Four sieve sizes were used to classify the powders: 220 μm, 425 μm, 850 μm, and

1150 µm, as seen in Figure 3. For sample production, a glass mold was utilized, as shown in Figure 4(a).

B. Sample Preparation Methods

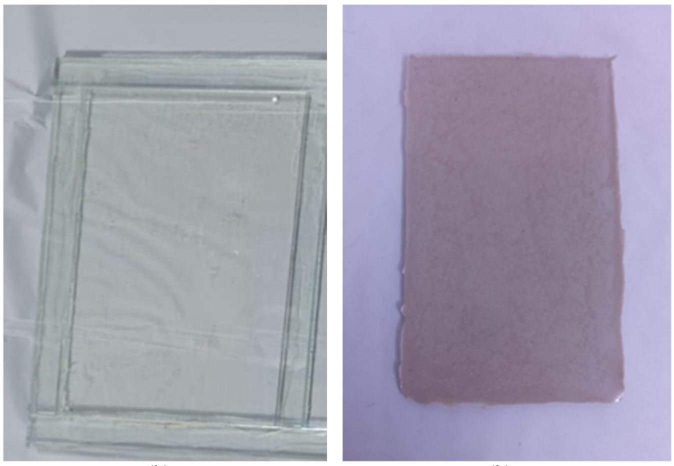
The initial preparation included a strict cleaning protocol where the eggshells and date seeds underwent multiple rinses with distilled water to eliminate potential contaminants and organic residues, as shown in Figure 1. The shells were air-dried at ambient temperature (23 ± 2 °C) for 24 hr to ensure complete dehumidification, as residual moisture can affect the matrix reinforcement interface. The volume reduction process (grinding or powder production) followed a carefully controlled sequence. The cleaned shells underwent preliminary crushing with a high-speed electric grinder to achieve coarse particles. These particles were then subjected to gradual grinding cycles until they reached the required size ranges. A mechanical sieve analysis system (VS-1, vertical oscillation type) operating at 280 oscillations per minute was used to separate the powder.

Fig. 2. Baron grinder used for sample preparation.

Fig. 3. Sieve and powder.

Different particle sizes powder was produced for both eggshells and date seeds using different sized sieves, where sizes of 220 µm ±15 µm, 425 µm ±15 µm were used for eggshells and 850 µm ±15 µm, 1150±15 µm for date seeds depending on the grindability of each material, as smaller sizes can be achieved in eggshells, unlike in date seeds.

The manufacturing protocol for composite samples followed a procedure that was systematically developed to ensure productivity and quality control [14-16]. A fine-formed glass mold system, as shown in Figure 4(a) was used, characterized by carefully controlled dimensions of 200 mm × 100 mm with a uniform thickness of 6 mm. Before composite preparation, the mold surfaces were subjected to treatment with a specialized release agent consisting of transparent silicone, followed by the application of a thin oil film barrier. The two-layer mold preparation method has proven to be essential to prevent sticking and facilitate the removal of clean samples after processing. The enhanced matrix mixing process involved accurate calculations of weight fractions based on predetermined proportions. Three distinct formulations were investigated: 35%, 45%, and 55% of the content of ESP and DSP, each prepared with the aforementioned particle size distributions. The mixing protocol included the initial mechanical mixing of epoxy resin with an accelerator in a carefully controlled ratio of 3:1. After that, the predetermined amount of powder was introduced gradually while maintaining constant agitation to ensure uniform dispersion. The produced sample is shown in Figure 4(b).



(b) (b)

Fig. 4. Sample and mold for testing: (a) glass mold, (b) ESP sample.

After the initial production process, multiple samples were prepared according to the criteria described later. Following tests were conducted on the samples in order to investigate the mechanical performance of ESP and DSP composites:

- Hardness Test: This test was conducted according to ASTM D-2240 specifications, utilizing a calibrated Shore-D durometer [17].
- Tensile Test: This test was performed based on ASTM D-638 standard [18-19].
- Impact Test: According to ISO 179 standard, with sample dimensions of 66 mm × 6 mm × 10 mm, using the Charpy effect [20].

- Flexural Test: Three-point test was performed according to ASTM D790 [21].

All these tests were carried out in the Materials Strength Laboratory of Materials Department, College of Engineering, Mustansiriyah University.

C. *Weight Fraction*

The weight fraction for each of the matrix (epoxy) and reinforcing materials (ESP and DSP) and relations are calculated by:

$$W_m = \frac{w_m}{w_c} \times 100\% \quad (1)$$

$$W_p = \frac{w_p}{w_c} \times 100\% \quad (2)$$

where w_m, w_c, and w_p are the weights of the matrix, composite, and reinforcement, respectively.

III. RESULTS AND DISCUSSIONS

A. *Hardness Test Results*

The hardness test results are presented in Table II.

TABLE II. HARDNESS TEST RESULTS

Weight fraction	35%	45%	55%
ESP 220 µm	89.1	91.2	115.3
ESP 425 µm	67.5	74.2	77.90
DSP 850 µm	76.1	81.5	100.3
DSP 1150 µm	70.1	84.7	96.4

Figure 5 shows the hardness of the samples for the eggshells and date seeds, for the aforementioned sizes, and at different weight fraction ratios. It is observed that the highest hardness occurred in ESP 220 µm and a at weight ratio of 55%. In this Test, ESP 220 µm achieved a significant hardness jump from 89.1 HV to 115.3 HV at 55%, indicating that a woven complex of enhancers had been formed after approximately 50% weight. In contrast, ESP 425 µm recorded a graduated linear increase from 67.5 HV to 77.9 HV without access to an enhanced network, due to the larger particle size or poor bonding to the matrix. The DSP 850 µm increased its hardness from 76.1 HV to 100.3 HV at 55%, in a pattern similar to the ESP 220 µm but starting at higher ratios, while the DSP 1150 µm provided a balance between the gradual increase and macular rise, rising from 70.1 HV to 96.4 HV.

B. *Tensile Test Results*

Figure 6 demonstrates that the DSP 850 µm has the highest yield stress with an increase of 35.1 MPa-58.2 MPa at 55%, followed by DSP 1150 µm, ESP 220 µm, and finally ESP 425 µm. The superior performance of the DSP 850 µm indicates its optimal size distribution and strong interface binding to the matrix, reducing the premature plastic deformation. ESP 425 remains the lowest, indicating that the weight gain alone is not enough without improving the dispersion and bonding. Figure 7 displays that the DSP 850 µm also tops the Young's modulus with a height of 13.2 GPa-18.6 GPa, which denotes a greater rigidity and ability to resist the elastic deformation. The tensile test results are presented in Table III.

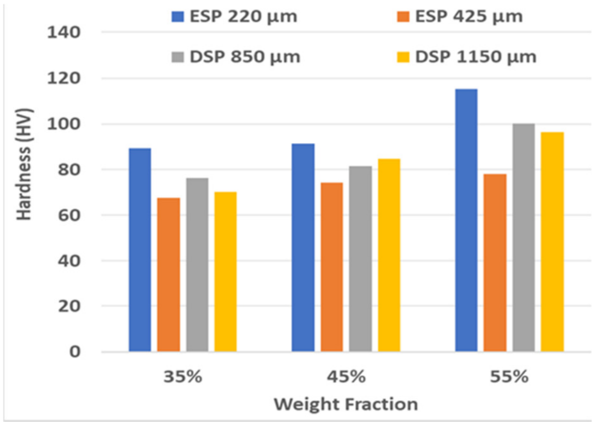


Fig. 5. Hardness results for ESP and DSP samples at different particle sizes and weight fractions.

TABLE III. TENSILE TEST RESULTS.

Sample	Weight fraction	35%	45%	55%
ESP 220 µm	Yield stress (MPa)	29.5	39.4	52.4
	Tensile modulus (GPa)	12.4	13.1	16.1
	Ultimate stress Mpa	31.8	47.0	57.7
ESP 425 µm	Yield stress (MPa)	32.4	41.5	49.2
	Young modulus (GPa)	11.8	14.3	15.8
	Ultimate stress MPa	33.4	47.8	59.04
DSP 850 µm	Yield stress (MPa)	35.1	41.7	58.2
	Young modulus (GPa)	13.2	17.8	18.6
	Ultimate stress MPa	37.2	54.9	67.3
DSP 1150 µm	Yield stress (MPa)	38.1	43.2	54.5
	Young modulus (GPa)	12.7	14.5	16.5
	Ultimate stress MPa	41.72	52.84	61.4

Regarding performance, the ESP 220 µm, DSP 1150 µm, and ESP 425 µm follow. A steep slope between 35% and 45% shows an initial entanglement phase of particles, while the gradual increase thereafter reflects a continuous linear reinforcement. The maximum stress results, as seen in Figure 8, reflect the material's endurance before failure, with the DSP recording an increase of 850 µm from 37.2 MPa to 67.3 MPa, outperforming the rest of the fractions. This is followed by DSP 1150 µm, ESP 425 µm, and ESP 220 µm. The high performance of the DSP 850 µm and DSP 1150 µm suggests an efficient lattice bonding and good particle dispersion, while ESP 220 µm and ESP 425 µm clarify limits at higher stresses, requiring adjustment of the size or surface of the booster to improve durability.

C. *Flexural Test Results*

The flexural test results are presented in Table IV. Figure 9 shows that the DSP 850 µm excels in flexural strength from 133.4 MPa at 35% to 165.8 MPa at 55%, indicating an optimal particle distribution and strong interface bonding with the matrix. It is followed by the ESP 220 µm, which rises from 118 MPa to 160.7 MPa, approaching the performance of the DSP 850 at the highest concentration. The DSP 1150 µm achieves a moderate increase from 122.5 MPa to 145.9 MPa, while the ESP 425 µm remains the lowest with a linear increase from 113.4 MPa to 135.4 MPa. This behavior reflects the importance of the particle size and dispersion homogeneity for high bending strength, where smaller particles (DSP 850) contribute to an improved surface tensile strength and stress distribution.

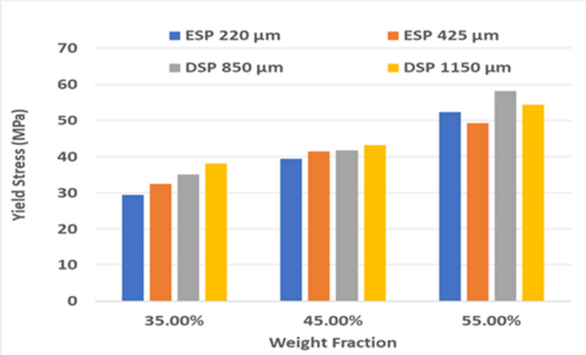


Fig. 6. Yield stress results for ESP 220 µm, ESP 425 µm, DSP 850 µm, and DSP 1150 µm.

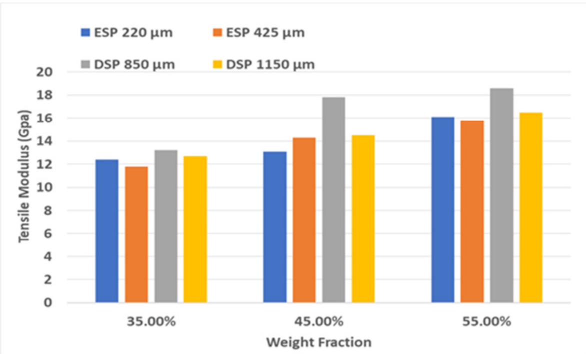


Fig. 7. Tensile modulus results for ESP 220 µm, ESP 425 µm, DSP 850 µm, and DSP 1150 µm.

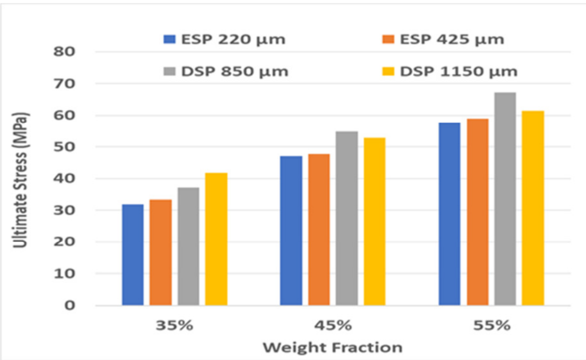


Fig. 8. Ultimate stress results for ESP 220 µm, ESP 425 µm, DSP 850 µm, and DSP 1150 µm.

TABLE IV. FLEXURAL TEST RESULTS

Weight fraction	35%	45%	55%
ESP 220 µm	118	132.1	160.7
ESP 425 µm	113.4	124.5	135.4
DSP 850 µm	133.4	162.6	165.8
DSP 1150 µm	122.5	139.7	145.9

D. Impact Test Results

The impact test results are shown in Table V and Figure 10.

Figure 10 demonstrates that the DSP 1150 µm achieves the highest impact strength with an increase of 11.8 to 16.9 J/cm² at 35%-55%, respectively, exhibiting an excellent dispersion and strong grip that facilitate the energy absorption under impact load. The impact strength of DSP 850 µm increased from 9.5 J/cm² to 14.5 J/cm², ranking second due to its relatively smaller particle size, which enhances dispersion and helps prevent the matrix cracking. ESP 220 µm and ESP 425 µm exhibited a moderate linear behavior, with impact strength increasing from 9.2 J/cm² to approximately 13 J/cm², reflecting the importance of the particle size and surface bonding for an improved impact resistance. The results reveal that increasing the booster ratio and improving its distribution enhance the energy absorption under shock.

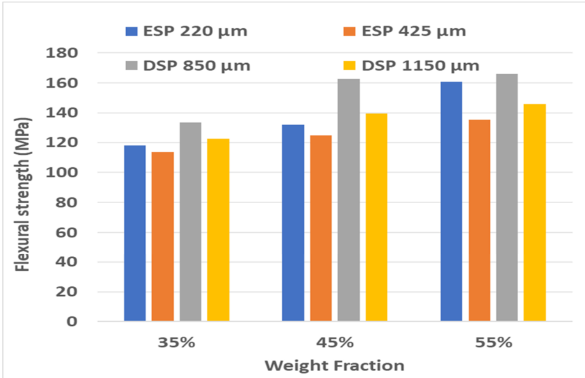


Fig. 9. Flexural strength results.

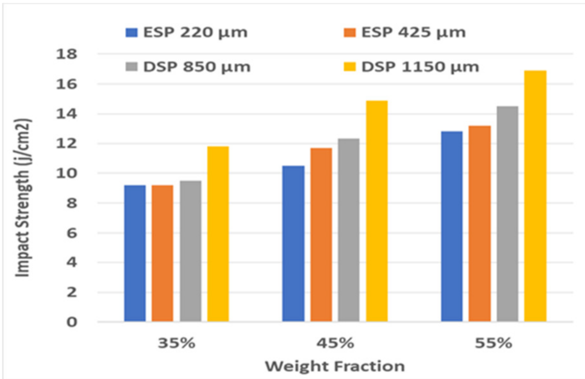


Fig. 10. Impact strength results for ESP 220 µm, ESP 425 µm, DSP 850 µm, and DSP 1150 µm.

TABLE V. IMPACT TEST RESULTS

Weight fraction	35%	45%	55%
ESP 220 µm	9.2	10.5	12.8
ESP 425 µm	9.2	11.7	13.2
DSP 850 µm	9.5	12.3	14.5
DSP 1150 µm	11.8	14.9	16.9

IV. CONCLUSIONS

This study investigates the mechanical properties of natural composite materials composed of epoxy reinforced with either Eggshell Powder (ESP) or Date Seed Powder (DSP), using two particle sizes for each filler (220 µm and 425 µm for ESP; 850 µm and 1180 µm for DSP) at weight fractions of 35%, 45%, and 55%. The main conclusions of this study are:

- Weight Fraction Effect: There is a general and consistent improvement in most mechanical properties (yield stress, Young's modulus, maximum stress, bending resistance, and impact resistance) with an increasing weight fraction of the reinforced materials. This suggests that increasing the proportion of particles in the matrix effectively contributes to improving the mechanical performance of the composite material.
- Particle size effect: The DSP 850 μm and DSP 1150 μm powders showed better performance in most properties compared to the ESP 220 μm and ESP 425 μm, especially in flexural and impact resistance. This is due to the better dispersion of larger particles and their uniform distribution within the matrix, reducing the stress concentrations and leading to a better distribution of the load.
- Best Overall Performance: DSP 850 μm recorded the highest values in most tests, especially in the yield stress, Young's modulus, and maximum stress, making it the best choice for applications requiring high rigidity and strength. The DSP 1150 μm is outstanding in impact resistance, rendering it ideal for applications requiring energy absorption and dynamic durability.
- Behavioral improvements: The differences between powders are most evident at the highest weight ratio (55%), suggesting that the effect of the particle distribution and bonding quality becomes more pronounced with a higher particle saturation within the matrix.
- The results revealed that smaller particles (ESP 220 μm) outperformed the larger in hardness (115.3 HV), while larger particles (DSP 1150 μm) excelled in the impact resistance (16.9 J/cm²) for their ability to absorb energy.

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