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Effect of pistacia khinjuk shell and rapeseed straw particles on mechanical properties and thermal properties of polyester-based composites

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HIGHLIGHTS

- Pistacia khinjuk and rapeseed straw fillers are attracting interest due to their biodegradability.
- Mechanical and thermal properties were studied in polyester composites with PK, RS, and hybrid fillers.
- Adding PK particles improved the tensile strength and thermal insulation of pure polyester composites.

Keywords:

Pistacia khinjuk shell
Rapeseed straw
Polyester
Hybrid composite
Mechanical properties

ABSTRACT

Composite materials are widely employed across various industries due to their superior mechanical and thermal properties compared to metals, offering improved performance with reduced weight. Polyester-based composites, in particular, have gained attention for their versatility and ease of processing, and their properties can be further enhanced by incorporating suitable fillers. In response to increasing environmental concerns, recent research has focused on natural fillers as sustainable alternatives, owing to their biodegradability, low cost, and minimal ecological impact. Despite growing interest, the combined application of underutilized bio-based materials, specifically Pistacia khinjuk (PK) shell particles and Rapeseed straw (RS) fibers within polyester matrices, remains largely unexplored. Addressing this gap, the present study investigates the mechanical and thermal properties of polyester composites reinforced with PK shell particles, RS particles, and hybrids. Fillers ranging from 53–300 µm were used, with PK content from 2 to 20 wt.% and RS at 2 wt.% and 5 wt.% in hybrid systems. Results indicate a 16.2% increase in tensile strength, reaching 40.81 MPa at 2 wt.% PK. In hybrid composites, the highest tensile strength of 37.97 MPa was observed at 2 wt.% RS + 2 wt.% PK. However, bending strength decreased with increasing filler content, while stiffness and thermal insulation improved. Thermal conductivity decreased to a minimum of 0.281 W/m.°C at 20 wt.% PK. SEM analysis revealed more uniform dispersion and stronger matrix adhesion of irregularly shaped PK particles compared to elongated RS fibers. Findings demonstrate that PK and RS are effective, sustainable fillers for enhancing polyester composite properties.

1. Introduction

Composite materials are increasingly important in various industries due to their versatile solutions and enhanced properties that meet different application requirements [1, 2]. They are typically formed by incorporating synthetic or natural materials as reinforcements or fillers; however, there is a growing shift toward natural materials as sustainable alternatives due to their ability to enhance physical and mechanical properties [3–5]. Natural reinforcement and filler materials are promoting sustainability and offer significant environmental benefits, such as; biodegradability, reduced energy consumption, lower processing costs, and minimal impact on human health and the environment [6]. They are derived from renewable sources such as plants, minerals, or waste materials. Lignocellulosic fibers have gained prominence as cost-effective and sustainable alternatives to synthetic fibers, demonstrating their versatility across industries such as automotive, sports, and packaging [7]. They also facilitate recycling processes and help reduce dependence on energy-intensive raw materials, aligning with the global push for sustainable manufacturing [8]. Therefore, various lignocellulosic fibers, derived from plants, like peanut shells, palm and coir, jute, rice husk, kenaf fiber, pistachio shells, nutshells, olive stones, sugarcane, Oak Sawdust, and bagasse, are increasingly used as reinforcements in polymer composites due to their ability to enhance physical and mechanical properties [9–13]. Pistacia khinjuk, commonly known as Baneh or Kolkhung, is a deciduous tree from the Anacardiaceous family, native to the Middle East and Mediterranean regions [14, 15]. Moreover, rapeseed straw, a byproduct of Brassica napus (rapeseed), is a readily available and

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cost-effective agricultural residue, with France ranking among the top five producers based on cultivated area. Although rapeseed is primarily grown for vegetable oil, animal feed, and biodiesel production [16], its straw remains underutilized despite its potential applications in particleboards, construction materials, insulation in construction, cladding, paper, packaging purposes, and biomaterials [17–19]. This study aims to investigate the thermal and mechanical properties of PK shell and RS particles and their effects on hybrid polyester-based composites at various weight fractions.

Natural fillers are renewable and cost-effective alternatives to synthetic or inorganic fillers and offer several advantages. Therefore, the researchers and manufacturers are increasingly focused on utilizing agricultural waste and residue particles as reinforcements in polymer composites. For example, Njoku et al. [20], evaluated the periwinkle shell-reinforced polyester composites fabricated by the hand lay-up technique. They found that the decrease in particle size improves both the tensile strength and Young's modulus, and indicated that smaller particles promote higher surface area and better stress transfer. Additionally, Nwigbo et al. [21], studied polyester composites reinforced with castor seed shells. They concluded that, compared to unreinforced polyester, a filler content of 30 wt.% improves tensile strength by 49%, while flexural strength decreases with increasing filler content. Moreover, a higher filler content enhances long-term creep durability by extending the time to failure. On the other hand, for polyester-based palm kernel shell (PKS) particulate composites, Shehu et al. [22], deduced that the highest tensile strength was recorded at 40 wt.% of the 300 µm particle size of the filler. Similarly, the impact energy increases with the increase of filler content for the particle size of 300 µm. Nayeeif et al. [23], conducted a study on composite materials using natural waste fillers, specifically sawdust and eggshell powder, combined with polyester resin to evaluate their mechanical properties under bending and tensile stresses. Polyester composites were fabricated with 30% and 40% by volume of each filler type. The study revealed that while the incorporation of these natural fillers decreased the tensile strength of the polyester matrix, it significantly improved its flexural strength. In a related study, Rautaray et al. [24], studied polyester composites with pistachio shell particles (PSP), finding improved tensile, flexural, and thermal properties, with maximum impact strength at 10 wt.% PSP filler content.

In addition, Mohammed et al. [25], investigated the composites unsaturated polyester reinforced with sunflower and watermelon seed shells at 75 µm particle size. They concluded that the flexural strength, modulus of elasticity, hardness, and compressive strength are improved with increasing shell powder content (wt.%) of the shell powder content. Abdullah [26], used sunflower husk and pomegranate husk particles as fillers in unsaturated polyester resin composites. He obtained that, compared to PP, the composite with 10 wt.% sunflower husks of 50 µm particle size achieves the best results, with 46.6 and 27.2% increases in tensile strength and Young's modulus, respectively. On the other hand, Ahlawat et al. [27], investigated walnut shell powder (WSP) reinforced polyester composites with particle sizes below 75µm. Tensile strength decreased from 21 MPa for neat polyester to 13 MPa at 30 wt.% WSP, while flexural strength declined from 24.2 to 16.3 MPa. In contrast, wear resistance improved with higher WSP content. Furthermore, Alsaadi et al. [28], explored the unsaturated polyester composites incorporating pistachio shell (PS) particles of less than 5 µm in size. Their findings showed that the tensile strength improved by 19.9% at a PS content of 10 wt.%, while the highest flexural strength and impact strength were observed at 5 wt.% PS. In other research, coir powder particles-reinforced polyester composites were investigated by Karthik Babu et al. [29], revealed that as the filler content increased, both the tensile and flexural strengths improved. Additionally, the highest tensile strength of 45.63 MPa was observed at 4 wt.% of coir, meaning an increase of 24.1% over the unfilled polyester. Similarly, the flexural strength peaked at 3 wt.% coir, with a 75.5% increase. Moreover, Adeyanju et al. [30], investigated the polyester composites reinforced with powdered snail shell (SNS) particles of sizes below 75 µm. They revealed that the highest flexural strength of 15.31 MPa was achieved at 15 wt.% SNS filler content, while the maximum flexural modulus of 710.36 MPa was obtained at 20 wt.% filler content. In addition, optimal abrasion resistance, indicated by minimal wear loss, was achieved at 5 wt.% filler content.

In another study, the polyester composites reinforced with hazelnut shell (HS), pistachio shell (PS), and apricot kernel shell (AKS) particles were examined by Çelik et al., [31]. Results showed that the tensile strength decreases with increasing reinforcement content, and the bending strength peaked at 10% reinforcement, especially with AKS. The compressive strength improved at moderate reinforcement levels, but declined at 30% due to poor matrix-reinforcement bonding, while thermal conductivity increased with filler content. Additionally, Pączkowski et al. [32], used peanut shell (PNS) powder as a natural filler in unsaturated polyester resin composites. The tensile and thermomechanical test outcomes showed that increasing PNS content enhances stiffness but reduces tensile strength. On the other hand, different studies examined RS particles, as fillers, to assess their impact on the properties of their polymeric composites [33–36]. Lendvai [37], investigated the mechanical properties of RS particles as a sustainable filler in bio-composites based on polylactic acid (PLA). Results showed that the tensile and flexural strengths decrease with increasing RS content, while the stiffness improves according to the increase of Young's modulus from 2.58 to 3.42 GPa by adding 20 wt.% of RSS. Hybrid composites have gained interest among researchers as an effective approach to enhancing composite properties. Combining two fillers with distinct structural, morphological, chemical, and physical characteristics offers advantages that neither filler alone can achieve in polymer matrix composites [38–42]. In a study by Essabir et al. [43], the coir fibers and their shell particles were applied as hybrid reinforcement in polypropylene (PP) hybrid composite. The composites were characterized through tensile and thermal tests. The best mechanical performance was observed at the 10:10 fiber-to-particle ratio, and the Young's modulus was improved by 50%. Previous reviews demonstrate that numerous studies have investigated the mechanical, thermal, and structural properties of composites reinforced with various individual and hybrid natural fillers. However, limited research has specifically examined PK shell particles in polyester composites or their hybridization with RS particles. This study addresses these gaps by evaluating the tensile and flexural properties, as well as the thermal conductivity and insulation performance, of composites reinforced with RS particles, PK shell particles, and their hybrid forms.

2. Experimental work

2.1 Materials preparation

Mature PK seeds were sourced from the local market, while rapeseed straw RS was harvested from a local farm in the Sulaymaniyah Governorate, Kurdistan Region of Iraq. The skins (coats) of the PK seeds were manually peeled, and the RS was subjected to a water retting process for 24 hours to initiate fiber separation. This retting process facilitated the breakdown of pectin and partial degradation of lignin, enabling the natural separation of fibers from the plant stems while preserving their structural integrity. The kernels were removed from the PK seeds, and the pith was extracted from the fibrous RS. Both the PK shells and RS fibers were then treated with a 1% sodium hydroxide (NaOH) solution for 3 hours. After the alkali treatment, the samples were thoroughly rinsed with distilled water at approximately 27 °C until a neutral pH (~7) was achieved. The treated materials were then oven-dried at 55 °C for 4 hours to eliminate any residual moisture. The dried PK shells and RS fibers were ground using a Chinese-made electric grinder, and the resulting particles were sieved using an RX-29-10 sieve shaker machine (manufactured in the USA) to obtain the desired particle size distributions. Figure 1 shows a flow chart illustrating the experimental procedure. The polymer matrix used in this study was Eskim ES-1060 polyester resin, with a density of 1.16 g/cm³, supplied by a Turkish company. The resin system included methyl ethyl ketone peroxide (MEKP) as the hardener and cobalt octoate as the accelerator to facilitate the curing process. Additionally, a platinum-based catalyst (of Turkish origin) and silicone rubber were employed for mold fabrication.

2.2 Test plan

To evaluate the impact of the proposed PK and RS particles on the mechanical and thermal conductivity properties of their polymer-based composites, various weight fraction ratios, as illustrated in Table 1, were considered for their individual or combined contributions as fillers. Accordingly, five test groups with a total of 15 tests were designed to compare their results with those of PrP in the first group. The proposed weight fractions of polyester, PK particles, RS particles, and their hybrids in the composites were determined based on literature and preliminary test results. These fractions were defined according to the rule of mixtures [26], as shown in Equations (1–4):

$$W_m = \frac{w_{polyester}}{w_{total}} \times 100 \quad (1)$$

$$W_p = \frac{w_{PK}+w_{RS}}{w_{total}} \times 100 \quad (2)$$

$$w_{total} = w_{PK} + w_{RS} + w_{polyester} \quad (3)$$

$$W_m + W_p = 1 \quad (4)$$

Based on the proposed applications of PK and RS filler-reinforced polymer composites in insulation boards, roof ceilings, automotive components, and furniture, their mechanical properties were defined through tensile and flexural tests, in addition to a thermal conductivity test.

Table 1: Weight percentage (wt.%) of polyester, fillers, and hybrid composites

Test Group	Sample code	Composition (weight fraction)		
		short (RS) fibers	(PK) shell	Polyester
		wt. %		
1	PrP	0	0	100
2	2%PK	0	2	98
	5%PK	0	5	95
	10%PK	0	10	90
	15%PK	0	15	85
	20%PK	0	20	80
3	2%RS	2	0	98
	5%RS	5	0	95
4	2%RS+2%PK	2	2	96
	2%RS+5%PK	2	5	93
	2%RS+10%PK	2	10	88
	2%RS+15%PK	2	15	83
5	5%RS+2%PK	5	2	93
	5%RS+5%PK	5	5	90
	5%RS+10%PK	5	10	85
	5%RS+15%PK	5	15	80

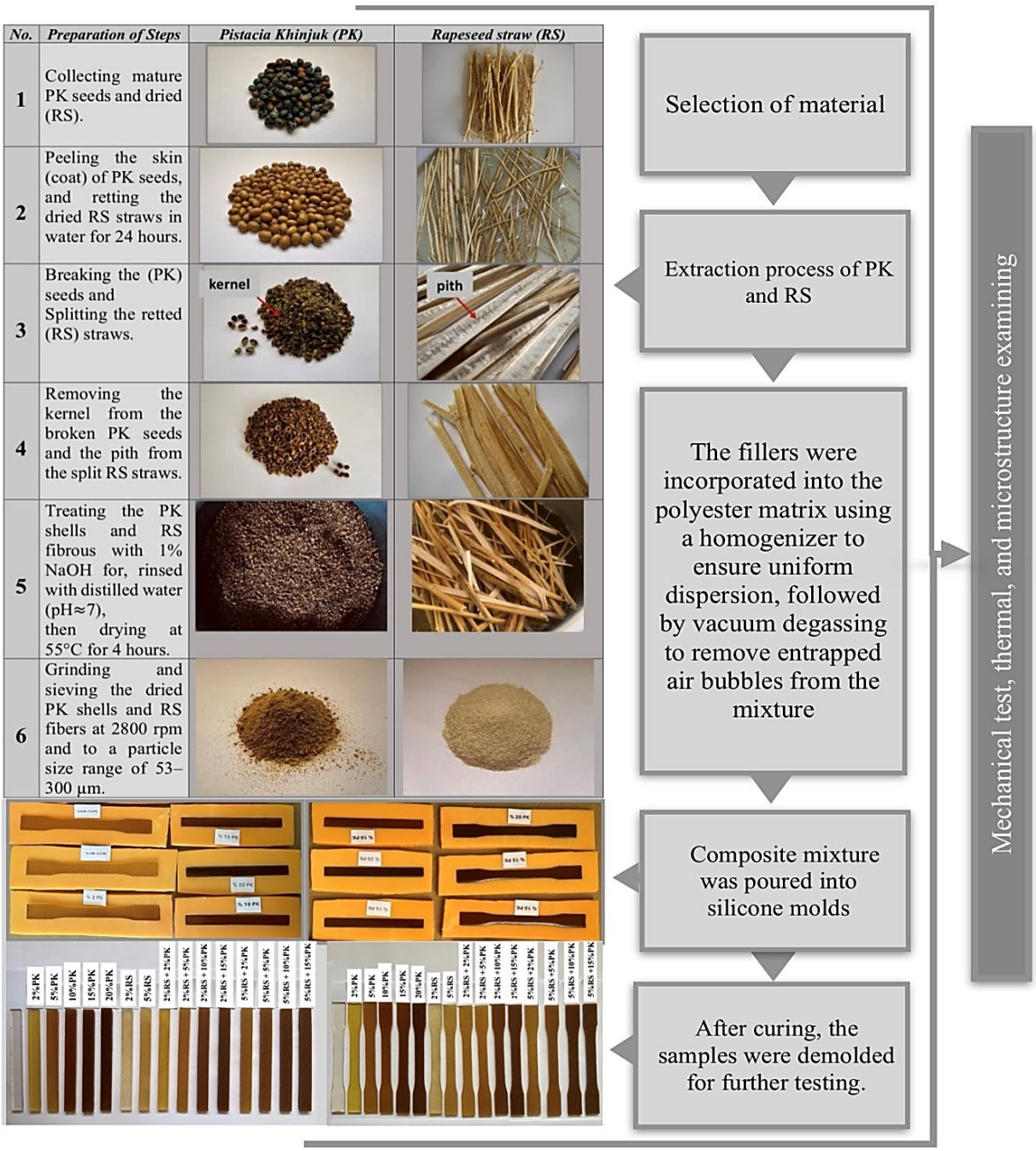

Figure 1: Schematic representation of the experimental procedure (flow chart)

2.3 Specimen Preparation

The dog-bone specimens for tensile testing shown in Figure 2(a), were prepared according to ASTM D638-01 standards [44], while the three-point bending test samples, Figure 2(b), were designed in accordance with ASTM D790 standards [45]. Additionally, thermal conductivity specimens were prepared according to the ASTM D7340-07 standard using Lee's disc method [46] as shown in Figure 2(c).

The flexible silicone rubber molds, as shown in Figure 3(a–c), were designed and fabricated according to the standard dimensions required for each specific test. Figure 3(a) shows the mold for tensile testing, Figure 3(b) presents the mold for flexural testing, and Figure 3(c) displays the mold for thermal conductivity testing. A 3D printer initially fabricated a sample model to be used as a template for preparing the desired mold. The silicone mold material was then prepared by mixing silicone and a platinum-based curing agent in a 1:1 weight ratio. The mixture was poured over the specimen models, and a vibrator was used to eliminate bubbles, ensuring a smooth, defect-free mold surface.

To prepare the composite test samples, the total weight of the mixture was determined initially, and the weight of each component was calculated using Equations 1- 4. The required weights of cobalt octoate and methyl ethyl ketone peroxide (MEKP) were determined to be 0.25% and 2% of the resin weight, respectively, according to the manufacturer's data sheet [47]. The polyester resin was first mixed with cobalt octoate and stirred for 2-3 minutes. Thereafter, the PK and RS particles were

added either individually or in combination, based on the composite systems, and the mixture was homogenized at 1000 rpm for 20 minutes to ensure uniform dispersion. Finally, MEKP was added and mixed at a low constant speed for 1-2 minutes. The prepared blend underwent vacuum degassing in two sequential steps of 10 minutes each, ensuring a total degassing duration of 20 minutes to remove the existing air bubbles. The final mixture was then poured into the molds' cavities and kept at room temperature for 24 hours for initial curing. After demolding, the composite specimens were stored at room temperature for two weeks to complete the curing process.

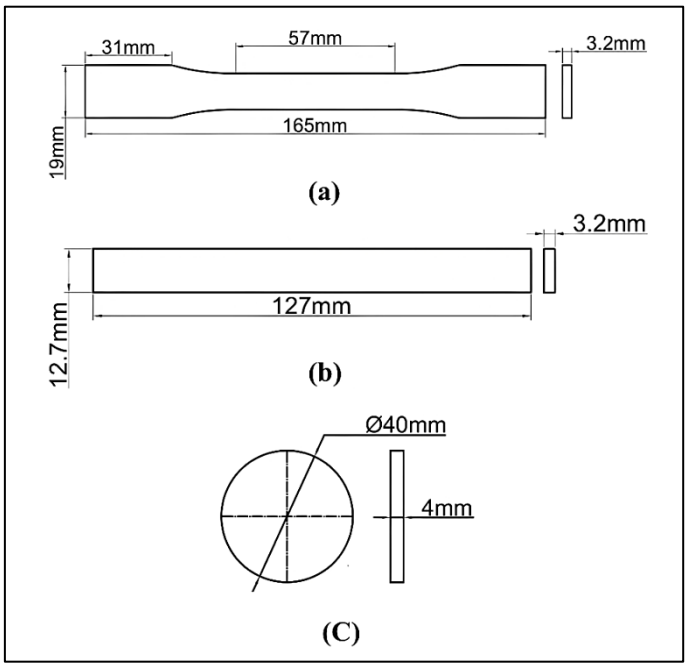

Figure 2: Standard shapes and dimensions of a) tensile, b) flexural, and c) thermal conductivity test specimens

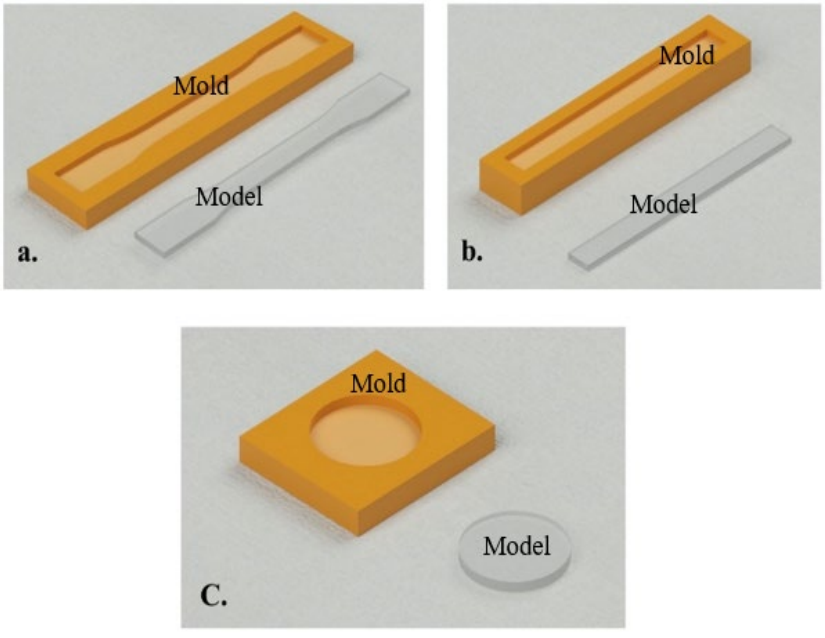

Figure 3: Molds of a) Tensile, b) Bending, and c) Thermal conductivity test samples

2.4 Tests and Inspections

2.4.1 Mechanical tests

The tensile tests were conducted using the Testometric universal testing machine, which has a maximum load capacity of 50 kN. The flexural tests were performed on the Cussons flexural testing machine, which is manufactured in the UK and has a maximum load capacity of 100 kN. The specimens were tested at room temperature with a crosshead speed of 1 mm/min. The span length for the flexural test was set to 51.2 mm. Figure 4 displays the tensile and flexural specimens before and after testing.

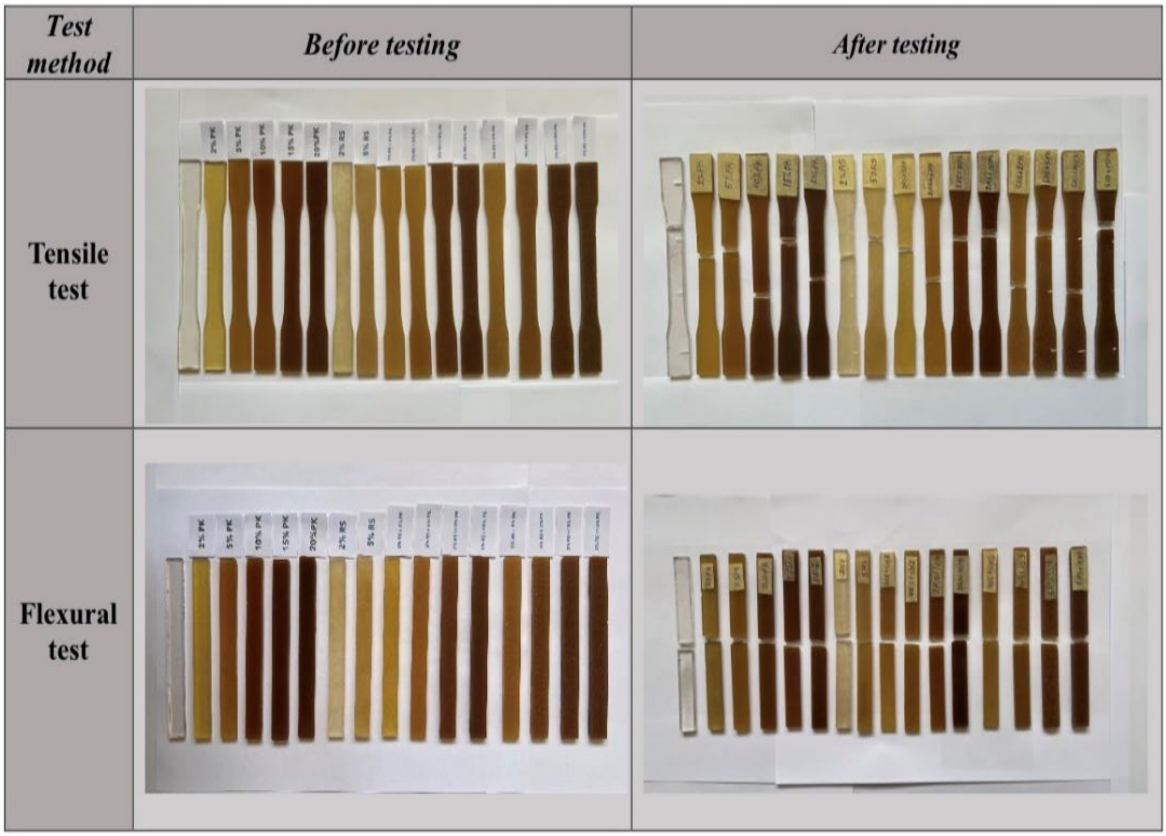

Figure 4: The mechanical test specimens were examined before and after testing

2.4.2 Thermal properties test procedure

Thermal conductivity measurements were performed using Lee's disc apparatus, manufactured by Griffin and George in England, as shown in Figure 5. The apparatus consists of three copper discs, each with a diameter of 40 mm and a thickness of 12.25 mm, along with an electric heater connected to a DC power supply. The test samples, as shown in Figure 6, are placed between discs A and B. At the same time, the electric heater is positioned between discs B and C. After operating the device for 30 minutes to achieve thermal equilibrium, heat was transferred from the heater to discs B and C, and then to disc A through the sample. The temperatures of discs A, B, and C (T_A, T_B, and T_C) were recorded using embedded thermometers, and the thermal conductivity of the samples was calculated in accordance with Equations (5) and (6) [48]:

$$k\left[\frac{T_B - T_A}{d_s}\right] = e\left[T_A + \frac{2}{r}\left(d_A + \frac{1}{4}d_s\right)T_A + \frac{1}{2r}d_s T_B\right] \quad (5)$$

$$H = IV = \pi r^2 e(T_A + T_B) + 2\pi re\left[d_A T_A + d_S \frac{1}{2}(T_A + T_B) + d_B T_B + d_C T_C\right] \quad (6)$$

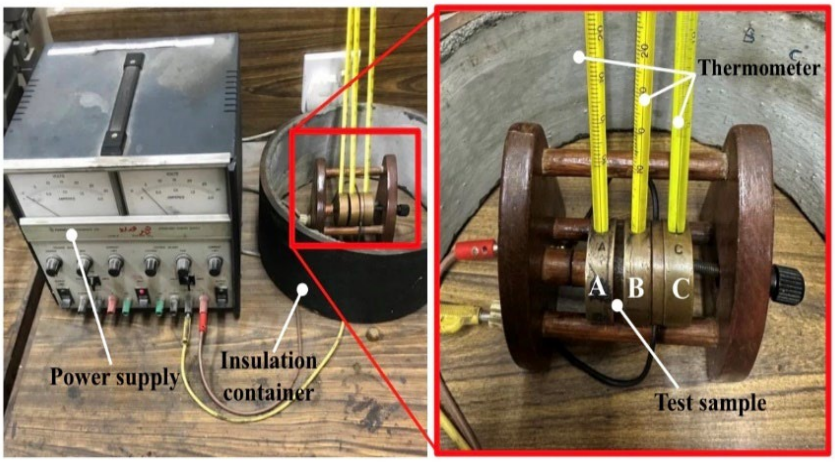

Figure 5: Thermal conductivity apparatus (Lee's disc method)

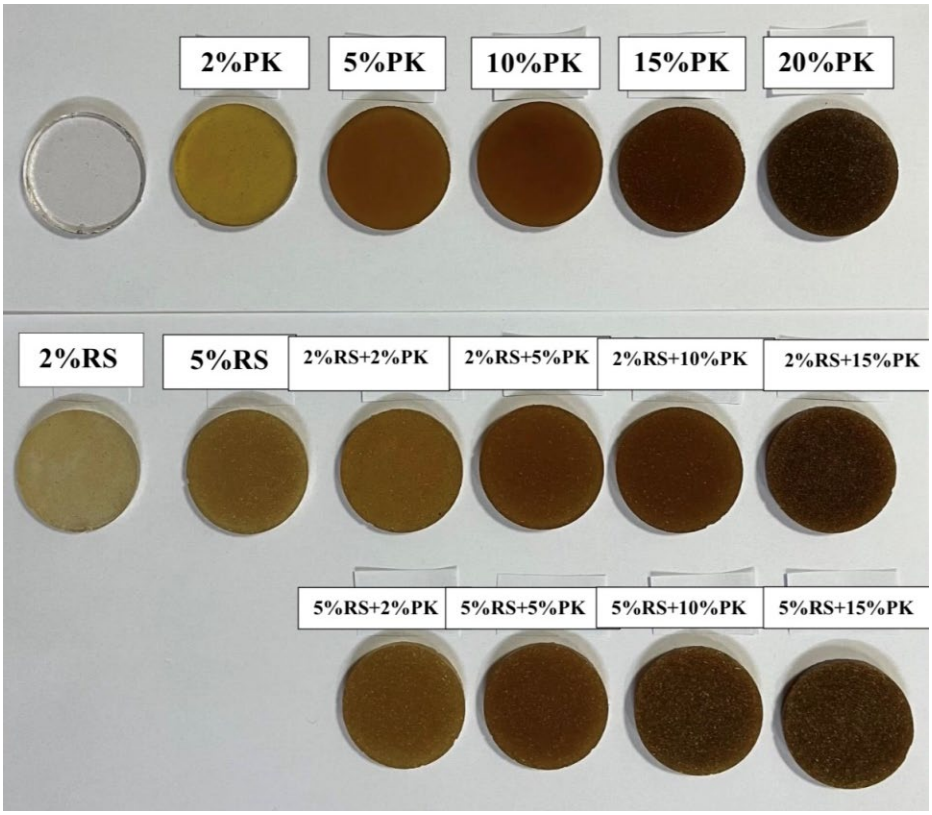

Figure 6: Samples of thermal conductivity tests

3. Results and discussion

3.1 Mechanical test

3.1.1 Tensile test

Figures 7, 8, and 9 present the stress–strain curves for composites reinforced with PK shell particles, RS particles, and their hybrid combinations. Interestingly, the addition of PK shell particles, individually and in combination with RS particles, leads to an overall enhancement in stress–strain performance.

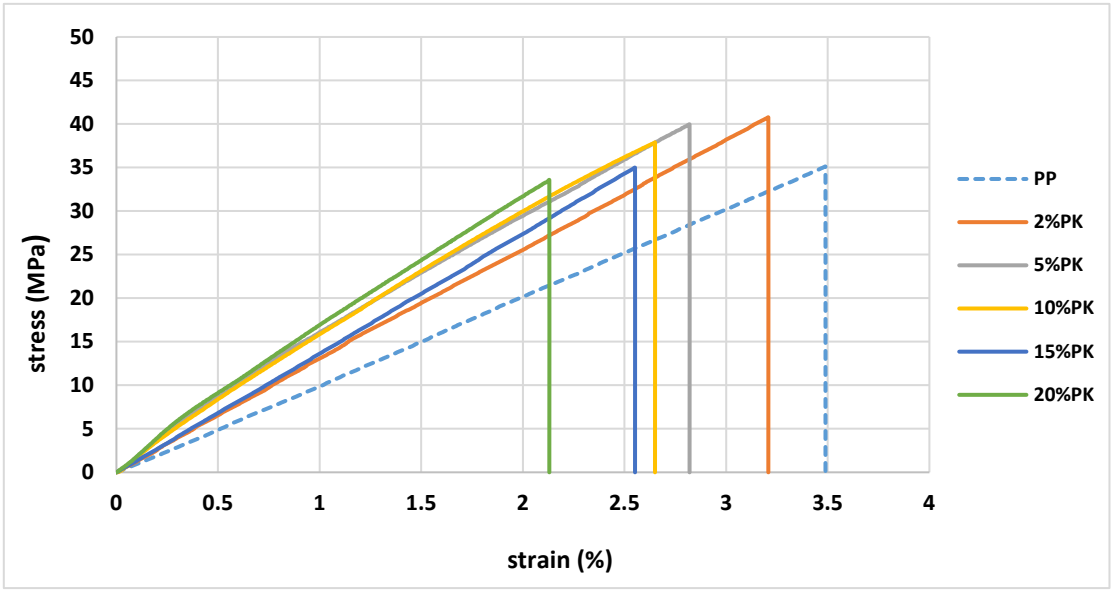

Figure 7: Stress-strain curves for pure polyester resin (PrP) and PK particle composites

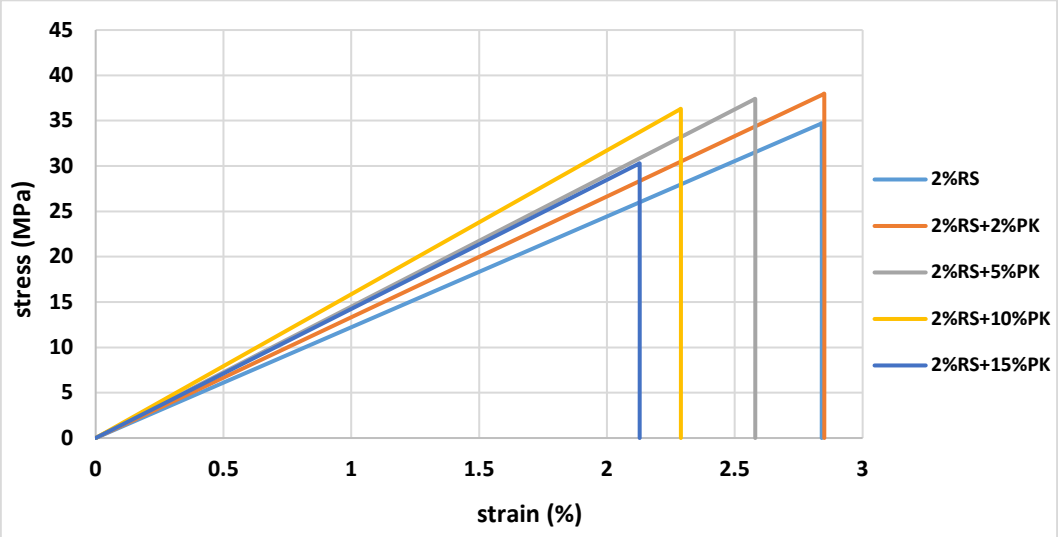

Figure 8: Stress-strain curves for 2 wt.% short RS fibers and the first combination of the hybrid composite

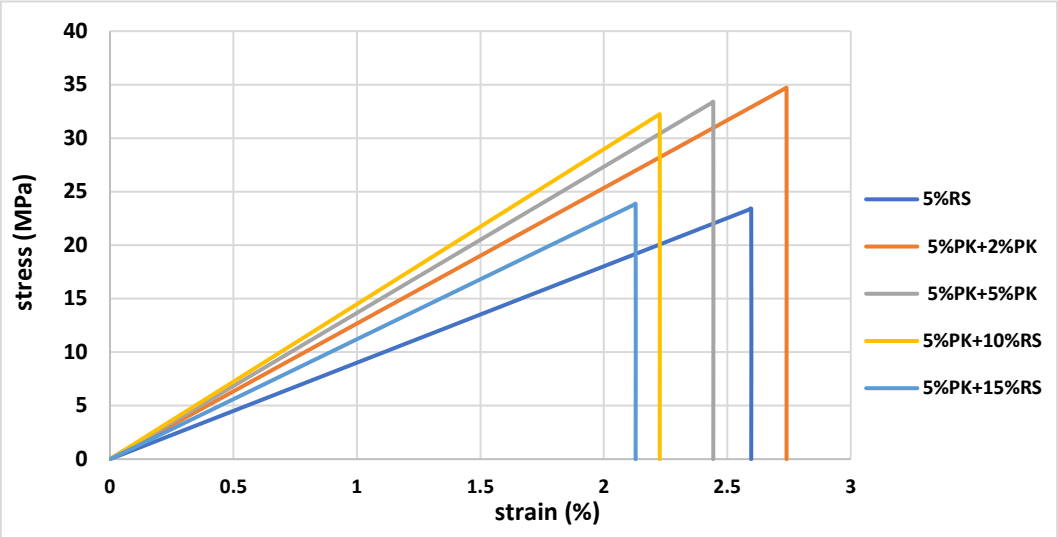

Figure 9: Stress-strain curves for 5 wt.% short RS fibers and the second combination of the hybrid composite

Figure 10 illustrates the effect of PK shell filler particles on the tensile strength and elongation at break of the polyester matrix. It shows that the tensile strength increases with PK particle inclusion, with the highest improvement observed at 2 wt.% PK particle content. At this concentration, the tensile strength reached 40.81 MPa, representing a 16.2% increase compared to pure polyester. Beyond this point, it begins to decline. This reduction in tensile strength can be attributed to the agglomeration of PK particles, which were not dispersed well. This poor dispersion hindered proper bonding between the agglomerated particles and the polyester matrix, leading to stress concentrations and, consequently, a decline in strength. The agglomerated filler particles act as barriers under stress, creating high stress concentration zones, particularly when interfacial compatibility is poor. Furthermore, an inverse relationship exists between PK shell content and elongation at break. This reduction in elongation suggests an increase in the brittleness of the composites.

The influence of RS particle inclusion on the tensile strength and elongation at break of the RS particle/ polyester composites is demonstrated in Figure 11. It presents that the increase of RS particles concentration slightly decreases the tensile strength of pure polyester to 34.7 MPa at 2 wt.%, and significantly drops to 23.4 MP at 5 wt. %. This decline can be attributed to poor interfacial adhesion between the matrix and the short RS fibers. Additionally, compared to that of PrP, the elongation at break of RS particle/ polyester composites drops from 3.5 mm to 1.97 mm at 5 wt. %, which is lower than that observed for PK particle/ polyester composites. The reduction in elongation was more pronounced for RS than for PK particles, which can be attributed to the elongated shape of RS.

Figures 12 and 13 present the ultimate tensile strength and elongation at break of the hybrid combinations. It can be observed that in the first combination, the incorporation of PK particles enhances the tensile strength compared to pure polyester, up to a filler content of 2% RS + 10% PK, after which the strength decreases with further increases in PK content. The highest tensile strength of 37.97 MPa was recorded at 2% RS + 2% PK, followed by a decreasing trend. Additionally, the elongation at break for both the first and second hybrid combinations decreases with increasing filler content.

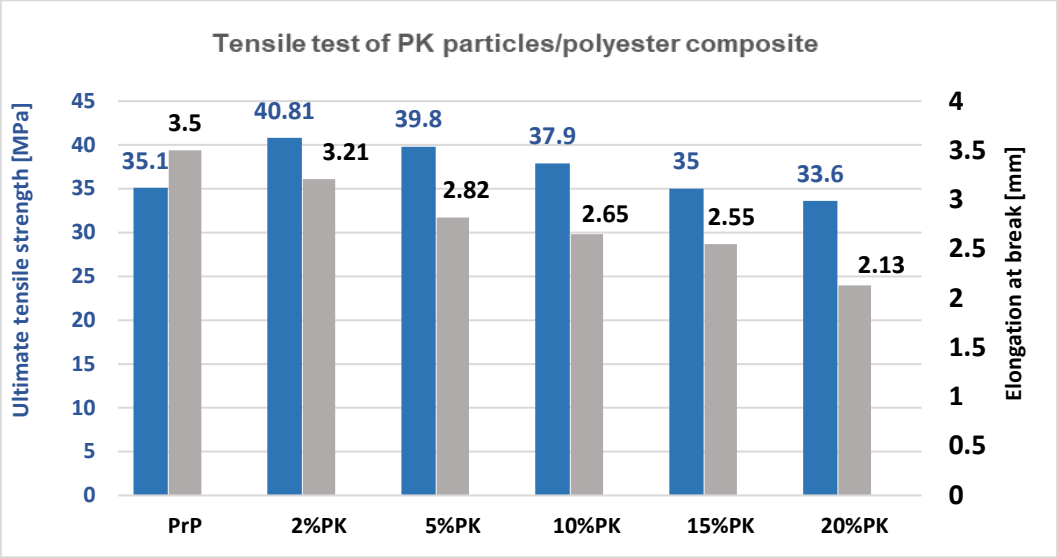

Figure 10: Effect of PK particle content on the UTS and elongation of PrP

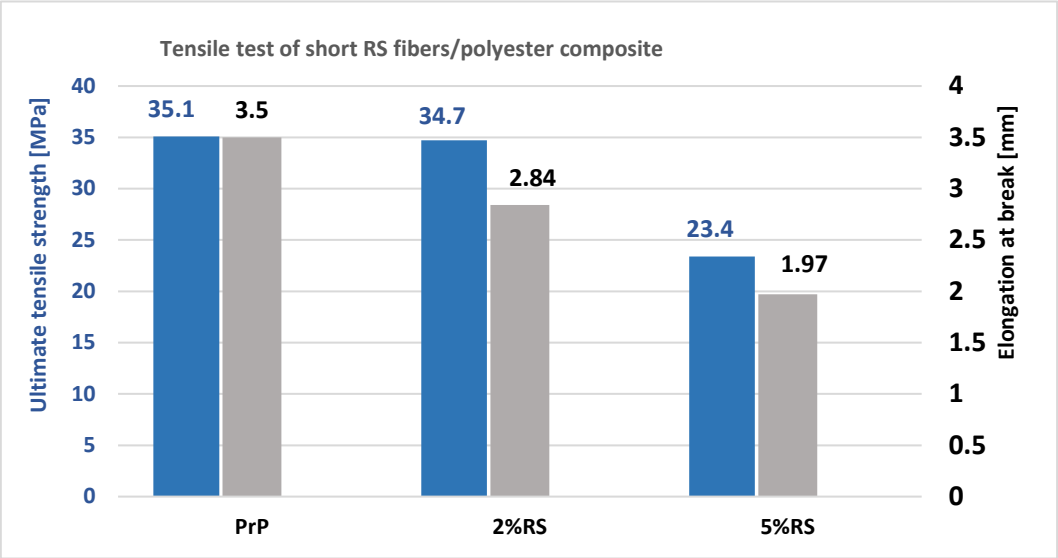

Figure 11: Effect of RS particle content on the UTS and elongation of PrP

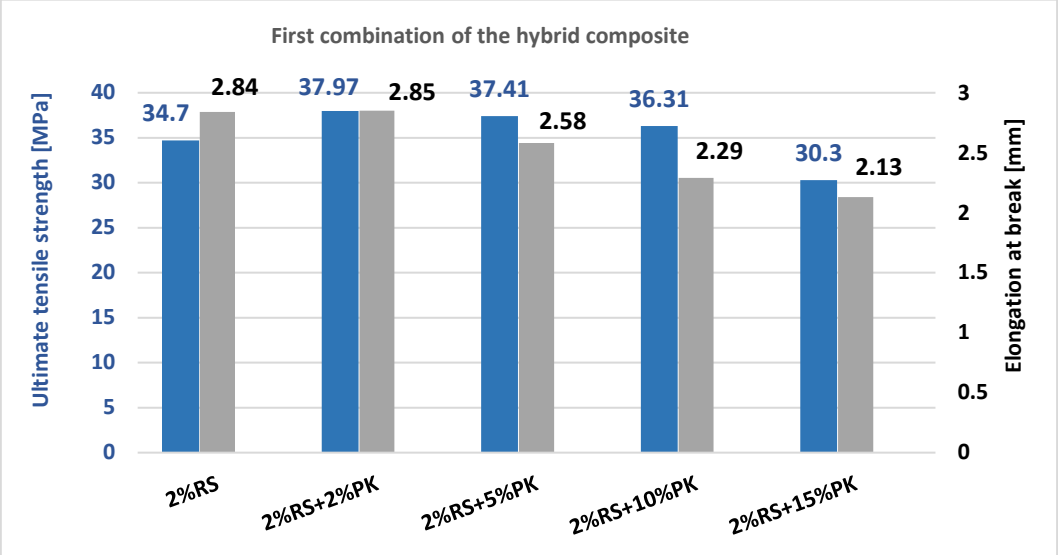

Figure 12: UTS and elongation at break of the first hybrid composite combinations

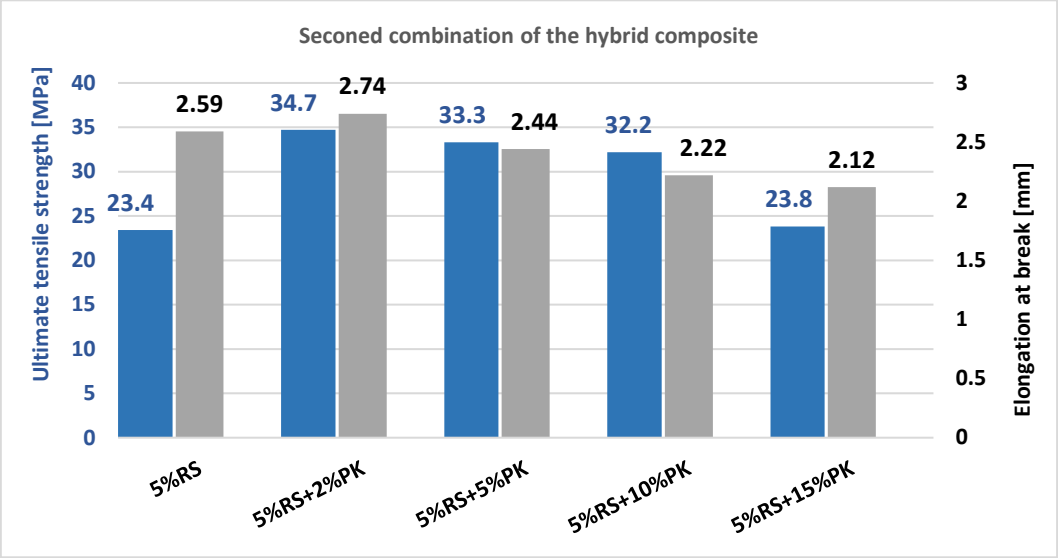

Figure 13: UTS and elongation at break of the second hybrid composite combinations

3.1.2 Bending test

Figures 14 and 15 show the peak bending strengths of PK and RS particles/ polyester composites, respectively, evaluated by applying the three-point bending test method. It can be observed that the bending strength generally declines as the filler content rises, but with various reduction percentages. For example, at 2 wt.% PK particles content, the bending strength of polyester/PK composites decreased from 120.5 MPa to 118.3 MPa, resulting in a reduction % of 1.82%. In contrast, at 2 wt.% RS the bending strength dropped to 90.0 MPa, corresponding to a reduction rate of 25.31%. The more pronounced reduction in bending strength induced by RS filler, compared to PK particles, can be attributed to differences in filler particle morphology. RS particles have a short, elongated shape (discussed in next section 3.3), whereas PK particles are approximately irregular and spherical (discussed in next section 3.3). This difference affects the uniformity and distribution of particles within the matrix. The irregular PK particles provide a better dispersion and higher particle-matrix interaction, enabling more effective stress transfer and enhanced composite strength. In contrast, the short, elongated RS particles tend to agglomerate, introducing flaws and creating voids within the composite structure, thereby weakening polymer-filler interfacial adhesion.

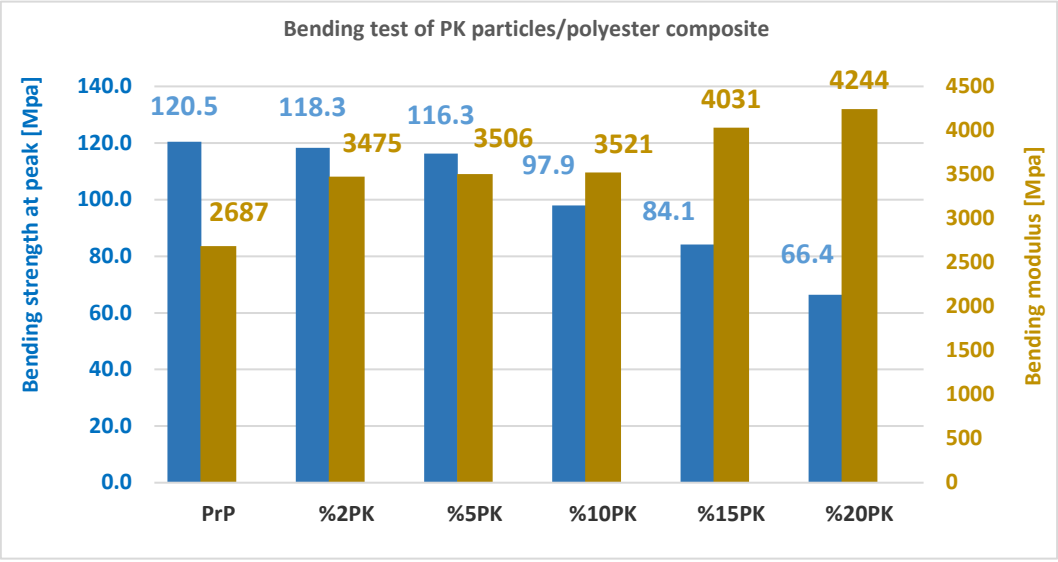

Figure 14: Effect of PK particle content on the bending strength and bending modulus of PrP

Additionally, the bending strength at the peak of both the hybrid composite combinations under the effect of the PK and RS particle content, as shown in Figures 16 and 17, is reduced with the increase of their contents. This observation in bending strength suggests that the measured strength is affected by two main factors: weak interfacial adhesion between the polymer and filler, and the agglomeration of composite components. However, the inclusion of these fillers increases the bending modulus overall. The highest value of 5039 MPa was observed for the hybrid composition containing 5 wt.% RS and 15 wt.% PK, indicating a significant improvement in stiffness. This enhancement is attributed to the presence of rigid particles, which exhibit much higher flexural stiffness compared to the polyester matrix. The agglomeration of PK particles and short RS fibers does not

affect the bending modulus (a measure of flexural stiffness) as it is measured at stress levels below those that encourage crack propagation in the agglomeration zones. This finding is in agreement with the findings of [49, 50].

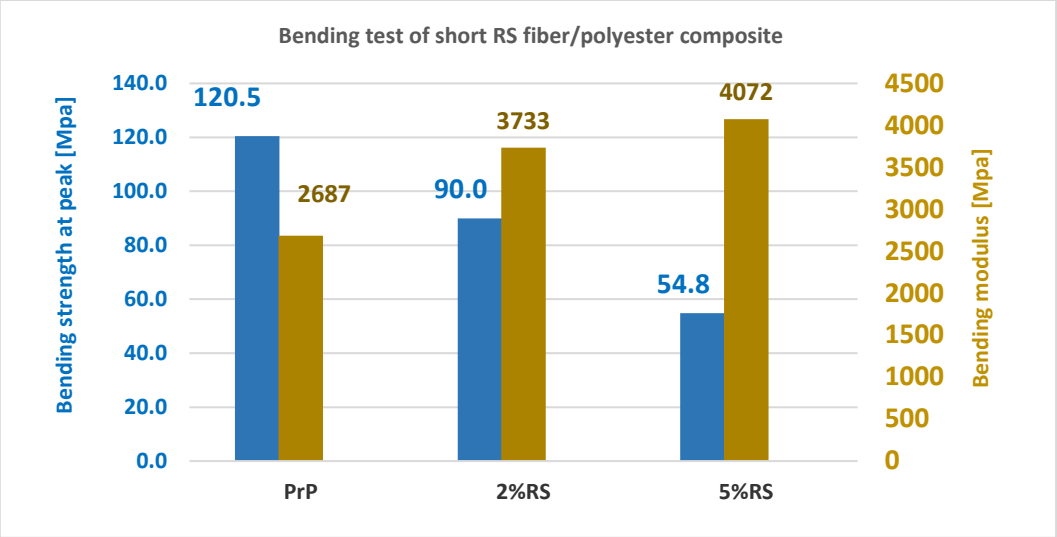

Figure 15: Effect of RS particle content on the bending strength and bending modulus of PrP

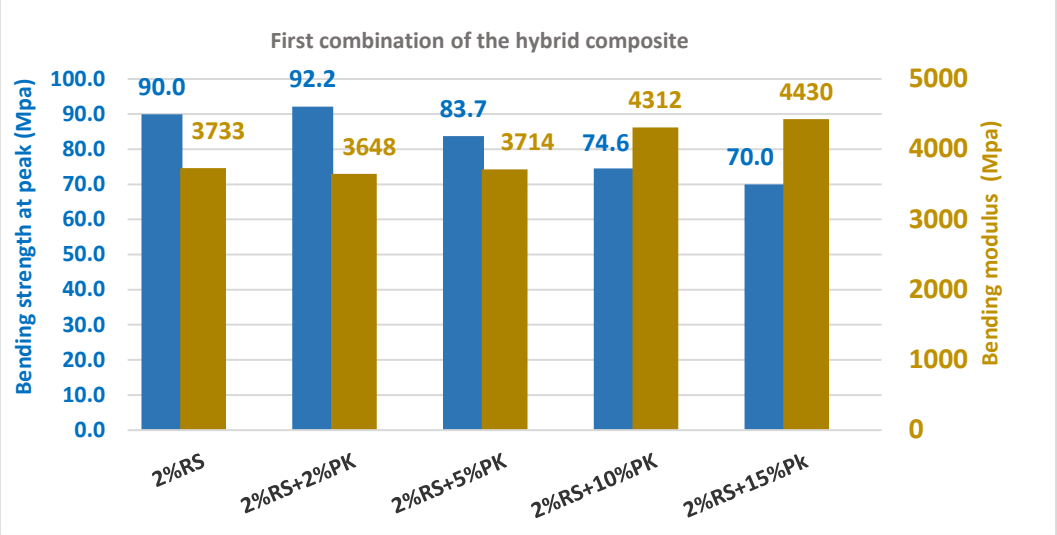

Figure 16: Bending strength and bending modulus of the first hybrid composite combination

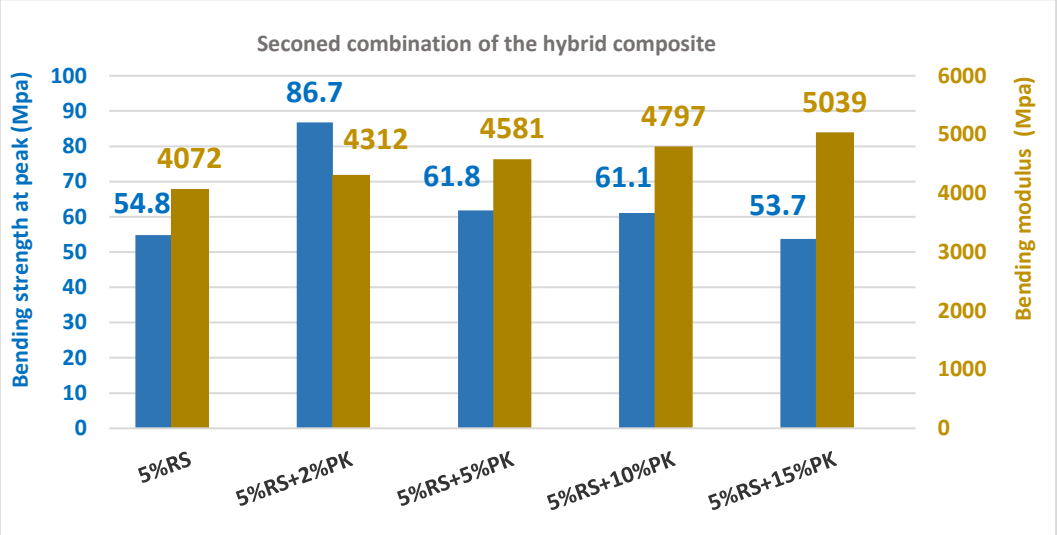

Figure 17: Bending strength and bending modulus of the second combination of the hybrid composite

3.2 Thermal conductivity

Thermal conductivity represents a material's ability to transfer heat, which is the opposite of its resistance to heat transfer. It is a crucial property in the design of insulating components across various industries. Figures 18 and 19 illustrate that thermal conductivity decreases linearly. The reduction in thermal conductivity with RS fibers is less significant compared to the irregular-shaped PK particles. The elongated structure of short RS fibers facilitates continuous heat transfer paths, resulting in a less significant reduction in thermal conductivity, as noted by Mishra et al. [51], thermal conductivity depends on the intrinsic thermal conductivity of the filler materials and the differences in particle geometries.

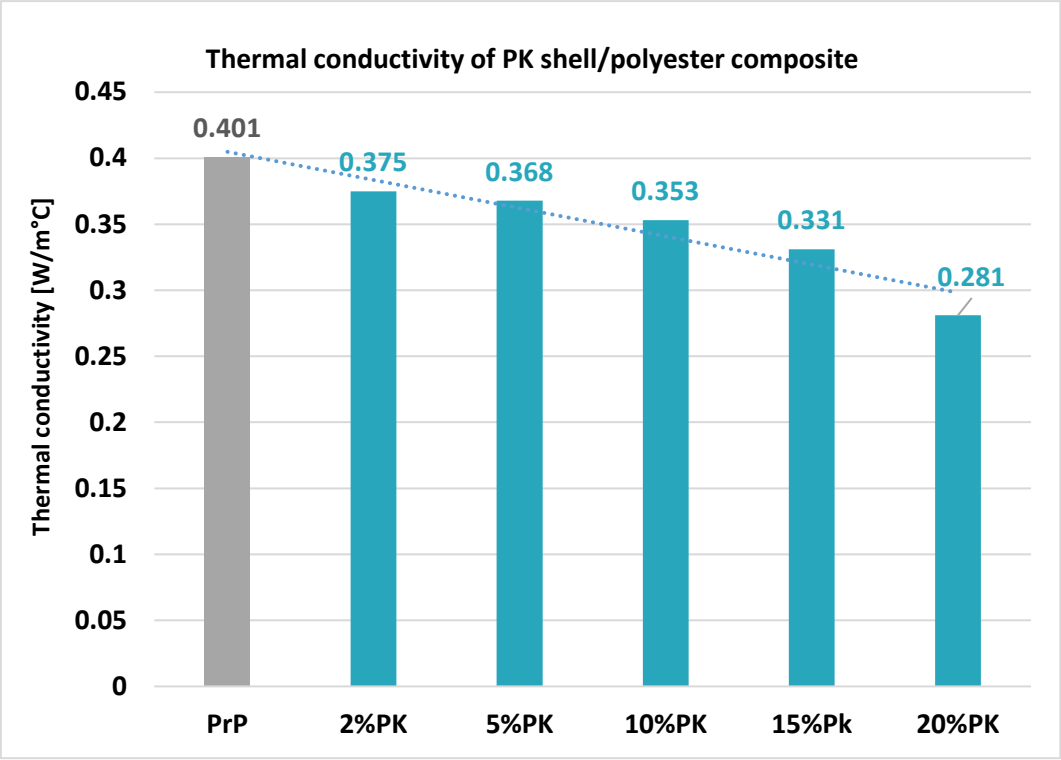

Figure 18: Effect of PK particles content on the thermal conductivity of PrP

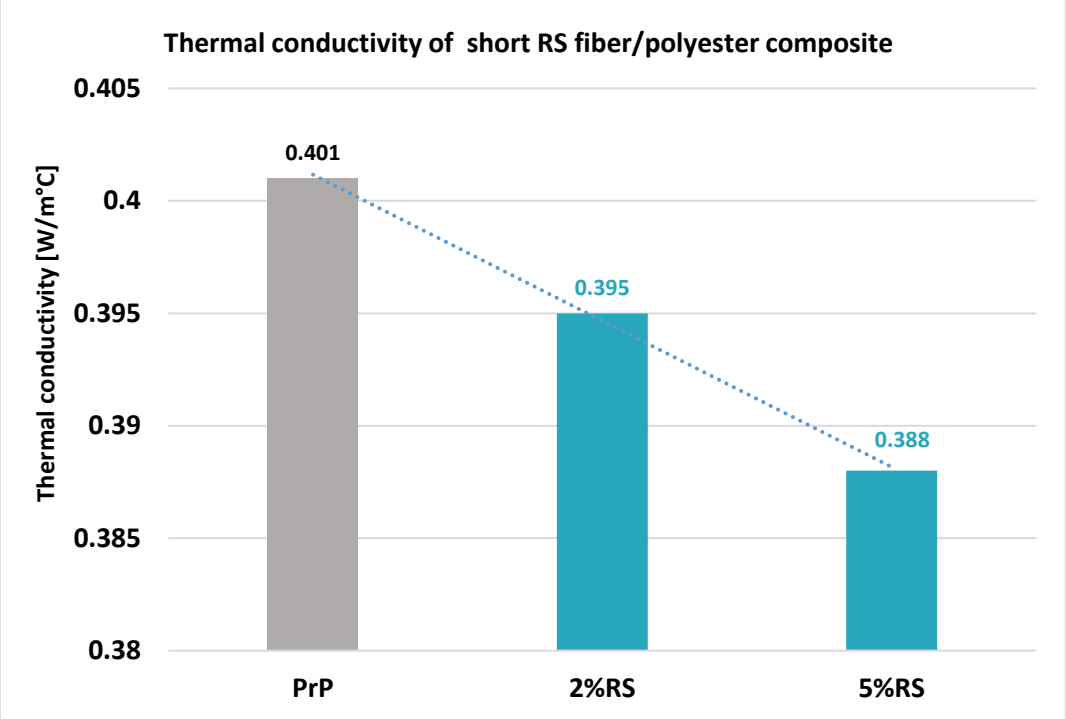

Figure 19: Effect of RS particle content on the thermal conductivity of PrP

In the hybrid composites, as shown in Figures 20 and 21, increasing the contents of both fillers exhibits a decreasing trend in thermal conductivity. The thermal conductivity of PrP decreases to 0.287 W/m.°C and 0.322 W/m.°C at 2RS + 15PK wt.% and 5RS+15PK wt.%, respectively. This behavior can be attributed to the way particles are arranged within the matrix, which is influenced by their shape, size, and formation of agglomerates, all of which impact the overall heat transfer performance of the composite system.

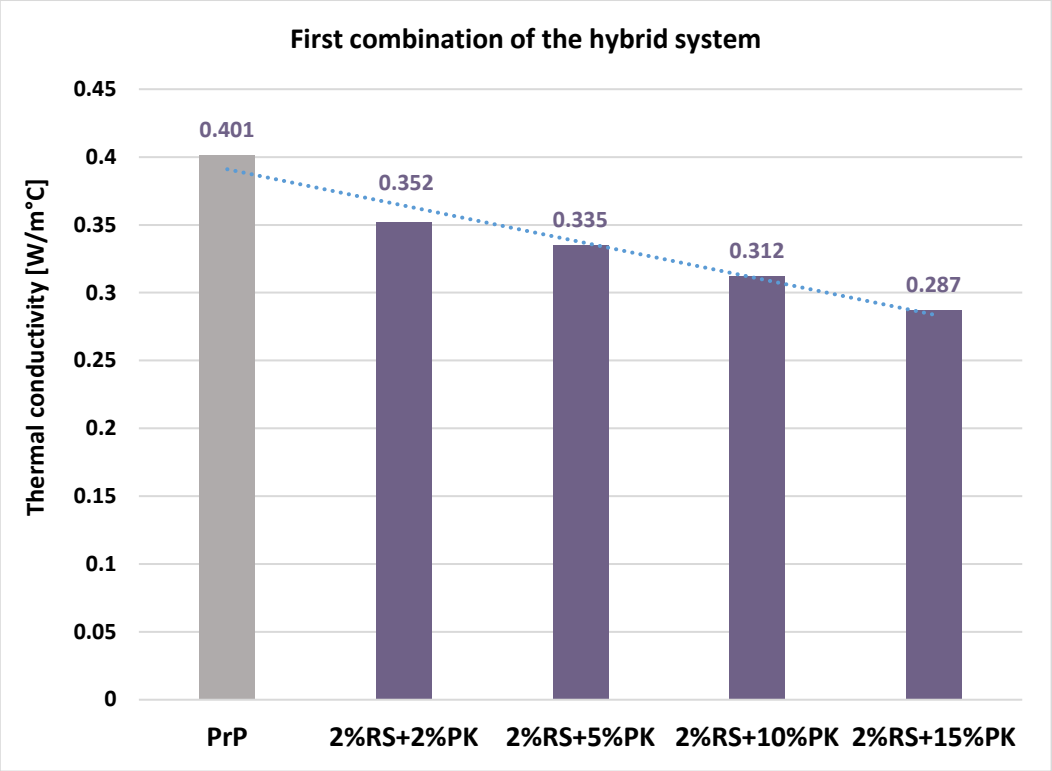

Figure 20: Thermal conductivity of the first hybrid composite combinations

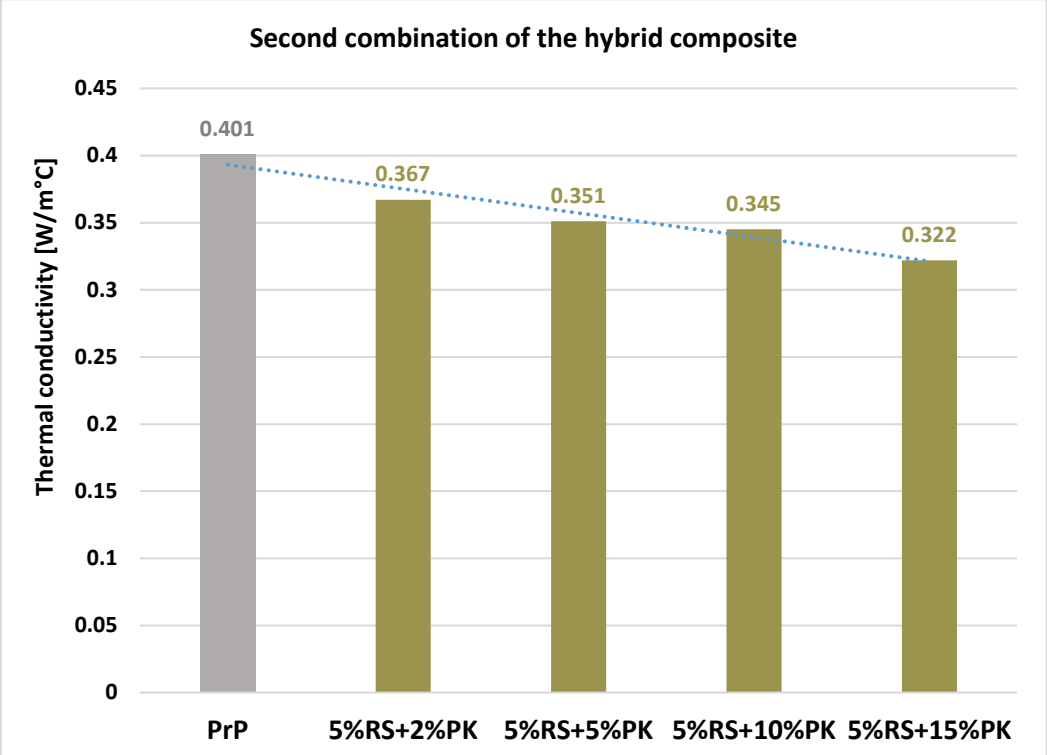

Figure 21: Thermal conductivity of the second hybrid composite combinations

3.3 SEM images analysis

The fractured surfaces of samples containing 2 wt.%, 5 wt.%, and 20 wt.% PK particles were analyzed using SEM (Figure 22) to evaluate particle shape, dispersion, distribution, and interaction with the matrix. The results indicate that the most uniform distribution of PK particles is achieved at a 2 wt.% concentration (Figure 22 a). Additionally, the PK particles exhibit an irregular spherical shape (Figure 22c), which enhances interfacial adhesion between the particles and the matrix. In contrast, at 5 wt.% and 20 wt.% PK content, agglomeration, and poor interfacial adhesion are observed. Furthermore, microcracks are present, which can lead to brittle failure at the interface between the PK particles and the polyester matrix, as shown in Figure 22 b and c.

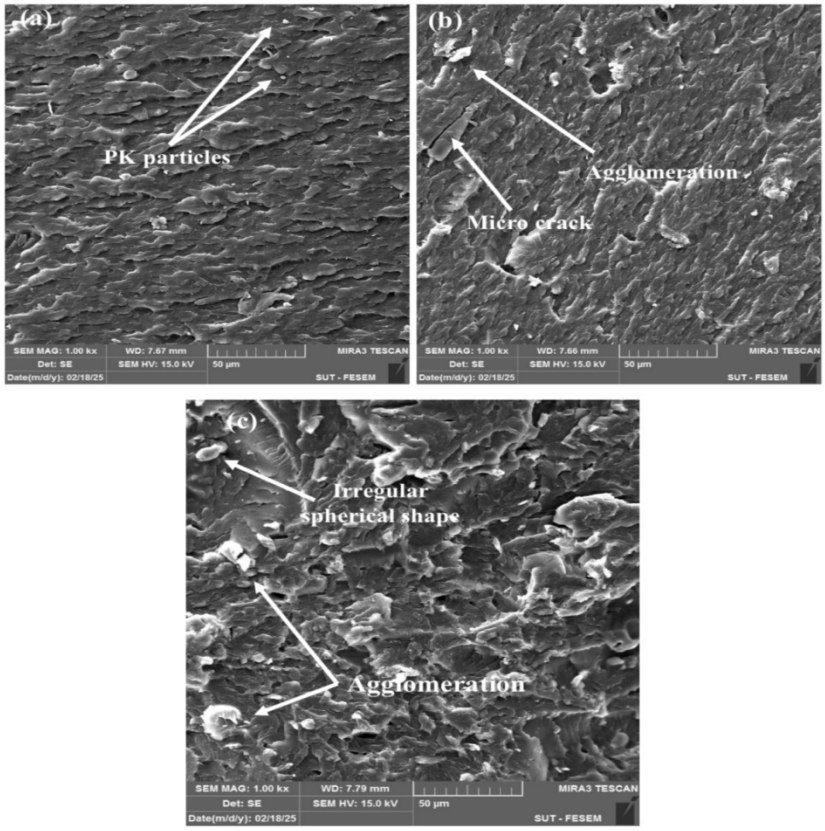

Figure 22: SEM images of the fractured surface of (a) 2 wt.% (b) 5 wt.% and (c) 20 wt.% PK particles content/ polyester composites

The SEM images of the fractured surface of 5 wt.% RS specimens are shown in Figure 23. Unlike PK particles, RS particles appear more like short fibers or elongated particles. Additionally, weak interfacial bonding between the RS filler and the matrix can lead to the formation of voids or pits due to debonding or the pull-out of RS particles. This indicates poor interfacial adhesion between the short RS fibers and the matrix. The elongated shape of the RS particles hinders effective bonding with the matrix and results in weaker interfacial adhesion with the polyester resin. In contrast, the irregular, rounded PK particles enhance their interaction with the polyester resin.

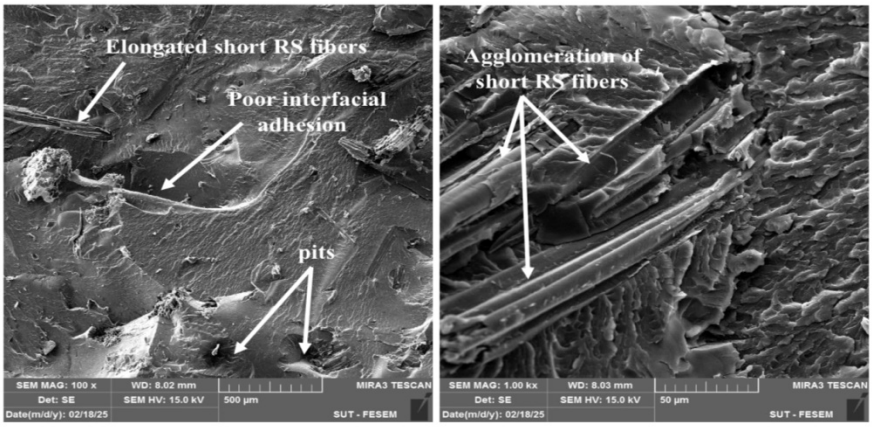

Figure 23: SEM images of the fractured surface of 5% RS particle content/ polyester composite

Figure 24 illustrates the structures of hybrid composites containing 2RS+2PK wt.%, 2RS+5PK wt.%, and 5RS+15PK wt.%, respectively. A uniform distribution of PK particles and short RS fibers, as shown in Figure 24 a, was observed at the low hybrid fiber content of 2RS+2PK wt.%. However, in the composites with higher filler content of 2RS+5PK wt.% and 5RS+15PK wt.%, a poor interfacial adhesion, as depicted in Figures 24 b and c, was observed.

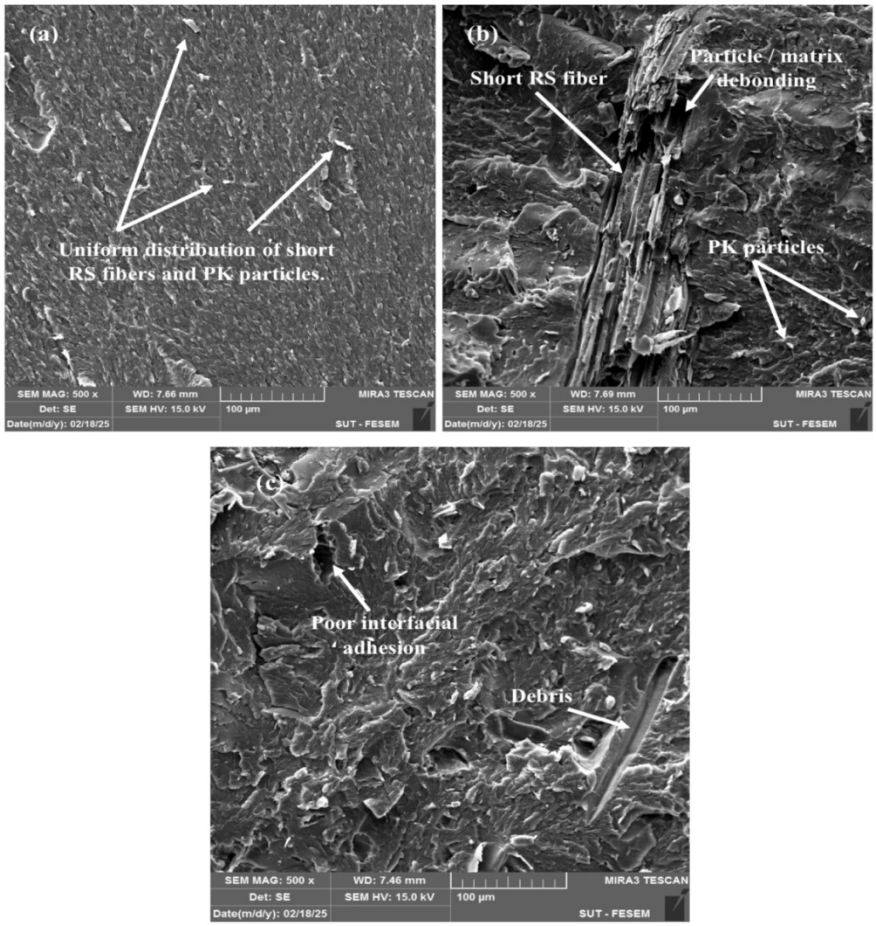

Figure 24: SEM images of the fractured surface of a) 2RS+2PK wt.%, b) 2RS+5PK wt.%, and c) 5RS+15PK wt.% particles/ polyester composites

4. Conclusion

The current study examined various polyester composites reinforced with individually and hybrid-produced particles, which were prepared at different weight percentages. Five levels of PK particles content, ranging from 2 to 20 wt.%, and two levels of RS content, incorporating 2 wt.% and 5 wt.% RS were selected. Additionally, their hybrid combinations were also proposed. The composites were tested to evaluate their mechanical properties and thermal conductivity under the impact of particle content ratios. The results led to the following conclusions:

1) The tensile strength of PrP increased with the addition of PK particles, reaching a maximum value of 40.81 MPa at 2 wt.% PK, representing a 16.2% improvement compared to PrP. Additionally, the incorporation of PK particles significantly enhanced the first hybrid combination, with the highest tensile strength of 37.97 MPa observed at 2 wt.% RS + 2 wt.% PK.
2) SEM analysis revealed that the RS particles are elongated and resemble short fibers, whereas the PK particles exhibit irregular, roughly spherical shapes. The results indicated that the irregularly shaped PK particles were more uniformly distributed within the matrix, while the elongated RS fibers showed poor interfacial adhesion with the polyester.
3) The elongation at break decreases with the addition of PK and RS particles, both individually and in combination. However, the reduction in elongation caused by short RS fibers is more significant than that caused by PK particles, likely due to the elongated shape of the RS fibers.
4) Adding individual and combined PK and RS particles to PrP decreases its bending strength while significantly increasing its stiffness. The highest bending modulus of 5039 MPa was observed with the hybrid composition of 5 wt.% RS + 15 wt.% PK.
5) The addition of PK particles and RS fibers decreased the thermal conductivity of the composites, thereby enhancing their thermal insulation properties. However, the reduction in thermal conductivity achieved with RS fibers was less significant than that with the PK particles. The lowest thermal conductivity, measured at 0.281 W/m·°C, was observed at 20 wt.% PK content.

Nomenclature

Symbol	Unit	Details
W_m	-	Weight percentage of matrix
W_p	-	Weight percentage of particles
w_{total}	g	Total weight of the mixture
$w_{polyester}$	g	Weight of the polyester resin
w_{PK}	g	Weight of the PK particles
w_{RS}	g	Weight of the RS particles
k	W/m.°C	The thermal conductivity coefficient.
d_s	mm	Sample thickness
T_A, T_B, and T_C	°C	Temperature of the copper discs respectively
r	mm	Radius of the disc
d_A, d_B and d_C	mm	The thickness of the discs, respectively.
e	W/m^2. °C	Heat transfer rate through the specimen's cross-sectional area.
I	Amp.	Current through the heater.
V	Volt	Voltage applied

Author contributions

Conceptualization, **S. Muhamadali,** and **R. Abdalrahman**; data curation, **S. Muhamadali,** and **R. Abdalrahman**; formal analysis, **S. Muhamadali,** and **R. Abdalrahman**; investigation, **S. Muhamadali**; methodology **S. Muhamadali,** and **R. Abdalrahman**; project administration, **R. Abdalrahman**; resources, **S. Muhamadali,** and **R. Abdalrahman**; supervision, **R. Abdalrahman**; validation, **S. Muhamadali,** and **R. Abdalrahman**; visualization, **S. Muhamadali**; writing – original draft, **S. Muhamadali**; writing – review and editing, **R. Abdalrahman**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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