Research Article

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Improving the thermal and mechanical features of polyester reinforced with orange peel waste micro-particles

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Abstract

Orange peel waste offers a potential particulate filler for polymer composites, but its influence depends on particle size, loading, and the property being considered. This experimental study examines polyester composites containing orange peel particles with nominal sizes of 125, 212, and 250 μm at mass fractions of 2, 4, 6, and 8 wt.%, alongside unfilled polyester. The peels were washed, oven-dried at 60 °C for 30 min, ground, and separated into the three size fractions before mixing and casting. The reported measurements comprise tensile stress–strain behavior, tensile strength, Young's modulus, flexural strength, Shore D hardness, and thermal conductivity. The summary plots indicate that the 125 μm fraction generally produced the highest values, with tensile strength, modulus, and flexural strength reaching their highest reported measurement values at 6 wt.%. Young's modulus increased from 385 to 674 MPa, whereas hardness increased from 36.8 to 66.36 Shore D units and reached its maximum at 8 wt.%. Thermal conductivity increased from 0.00109 to 0.03673 W/(m·K). The tensile-strength summary reports an increase from 29.504 to 50.592 MPa, although its unfilled reference conflicts with the stress–strain curves and requires reconciliation. The results suggest property-specific responses rather than a single optimum formulation: additional filler beyond 6 wt.% reduced several mechanical responses while hardness and conductivity continued to increase for the smallest particles. Missing uncertainty estimates and an unresolved tensile-reference discrepancy limit quantitative interpretation. The findings support further evaluation of orange peel as a polyester filler, without establishing biodegradability, improved thermal insulation, or application-level performance.

Keywords: Orange Peel Waste; Polyester Composites; Particle Size; Mechanical Properties; Shore D Hardness; Thermal Conductivity

1. INTRODUCTION

The reuse of valuable materials obtained from food-processing wastes has spurred increased interest in using natural fillers made of plants for composites made of polymers. Orange peel is an excellent example of such a residue since it can be crushed to produce particles that can then be used in a polymer matrix. The study of orange peel both as an active filler and as a supplier of natural materials shows that there is more to this residue than just recycling [1, 2]. However, just the use of a renewable filler does not necessarily make the composite biodegradable or environmentally friendly.

Studies concerning orange peel biofilms and other studies on fruit waste based bioplastics situate this approach in a larger project of recovering valuable components from agricultural waste [3, 4]. Such studies as development of carboxymethylcellulose packaging materials, starch/chitosan films loaded with anthocyanin extracts, and natural biocomposites produced from banana plants represent a few examples of such projects [5–7]. These are all very different in matrix composition and preparation methods; however, that makes these studies a context in the field of waste recycling rather than the predictors of stiffness and thermal conductivity of orange peel filled polyester matrix. This point is crucial since the presence of plant-based filler inside synthetic polymer thermoset does not exhibit similar degradation as in the case of a film based on renewable polymers.

A particulate composite can be described as a system with matrix and dispersed solid phase with an interface at which the transfer of stress and heat is possible. The combination of phases may lead to the enhancement of stiffness, strength, hardness, and transport properties; however, it should be noted that improvement in all these properties is not obligatory. A number of studies has already been performed in relation to Sidr leaf particles, animal horn particles, and waste marble particles added into the polyester matrix [8–10]. Additional examples of fillers added into polyester matrices are silica fume, glass powder, carbon black, and glass with natural waste fibers [11–13].

Particle size will determine the extent of the interfacial area per unit weight of filler, as well as affect wetting, packing, and agglomeration tendencies. Loading will increase the presence of load-bearing inclusions, while increasing viscosity and complicating uniform distribution. Processing studies on Zea-fiber composites and biocomposites with wood particles reinforce the need to consider processing and reinforcement issues [14, 15]. Work on bamboo/jute-polyester composites and on natural-fiber composites for ballistic application considers other reinforcements' geometry and characteristics [16, 17]. Findings with regard to continuous or woven fibers cannot simply be applied to irregular orange peel microparticles with their specific defect load transfer mechanisms.

The research with regard to the modification of other thermosetting resins with particles will provide a perspective to understanding the difference. This concerns work on polystyrene–graphene-oxide particles in epoxy resin, activated carbon in epoxy resin, and polyetheretherketone particles in carbon/epoxy composites [18–20]. The hybrid sisal fiber/epoxy systems with e-waste nanofillers and epoxy composite with silica modified graphene oxide provide additional insight into the effect of interfaces, particle morphology, and preparation methods [21, 22]. However, these examples will not prove the mechanism of loading in orange peel particles-polyester system. Rather, they will prove the necessity to differentiate the two types of effects.

Recent studies of additions from plants to unsaturated polyester are particularly important for the present material system [23]. The impact of testing conditions is also demonstrated by the research on natural-particle composites subjected to cryogenic testing and natural-particle additions to epoxy-polyurethane alloys at various temperatures [24, 25]. Comparisons of studies, therefore, should take into account such issues as matrix composition, filler treatment, shape and size of test samples, conditioning of specimens, and methodological details of testing. Identical values of numerical characteristics do not mean identical properties of materials when the above factors differ. Similarly, any suggestion about applicability of the material for some industrial or construction use should be verified by testing under service conditions.

The present investigation focuses on dependencies of mechanical characteristics and thermal conductivity of polyester composites on three sizes of orange peel particles and four mass fractions of fillers. It is necessary to understand if there is a consistency of changes of different properties, which means an increase of each due to an increase of the filler fraction, or if each property prefers certain formulation. Comparison of the experimental results is done using unfilled polyester as the reference material. Attention should be paid to the difference between the maximum value in the tested range and generally optimal composition.

2. MATERIALS AND METHODS

In this work, polyester resin was used as the continuous matrix, while orange peel was used as particulate reinforcement. Orange peel was thoroughly cleaned with distilled water, followed by drying in hot-air oven at 60 °C for 30 minutes. After drying, orange peel was ground by means of an electric grinder, and particles of different nominal particle sizes (125, 212, and 250 μm) were obtained. It should be noted that the listed numbers indicate the nominal sizes of the particles, but not their mean diameter. In addition, there was no information about the actual particle-size distribution. Drying temperature and time do not guarantee the achievement of constant residual moisture content of particles.

It is important to note that, in this case, the preparation method is characterized by dispersing solid orange peel particles in the polyester to obtain the particulate composite with a continuous polyester matrix. There is no information about the chemical surface treatment of particles. Information about the particle morphology, particle-size distribution width, and surface composition was not provided; therefore, information about the particle packing and interface contact is based on the bulk properties.

Composite was made with mass fractions of 0.02, 0.04, 0.06, and 0.08 corresponding to 2, 4, 6, and 8 wt.%. The preparation of powdered mixture of particles with polyester and pouring into molds for the mechanical and thermal measurements was performed at each size fraction. For unfilled composite, the mass fraction is equal to zero. The specified design includes 12 filled composite formulations and one unfilled composite formulation.

The comparison is carried out depending on the particle size for each loading level and depending on the loading level for each particle size fraction. The reported mass fractions are used as they are written in the paper. Nevertheless, the question about the calculation basis remains open: curing additive might have been added during composite formation, and thus, the total mass of the formulated composite could not be used to calculate mass fraction. The grade of resin, curing agent, mixing time, mixing rate, degassing and curing conditions, which are crucial for reproducibility, were not documented. These variables can have an impact on void formation and mechanical behavior of the matrix.

The characterization of the obtained composite includes tensile stress-strain curves, tensile strength, Young's modulus, flexural strength, hardness, and thermal conductivity. The tensile strength and modulus are reported in MPa. On the original hardness chart, the Shore D hardness scale was specified, while the thermal conductivity is reported in W/(m·K). Evaluation of the density was based on the Archimedes' principle; however, the values of density were not reported; thus, the reduction in density or increase in specific strength was not evaluated.

Results are evaluated descriptively because replicate counts, standard deviations, confidence intervals, and other uncertainty estimates are unavailable. Smooth connecting lines in the figures are treated as visual guides and not as validated models of intermediate compositions. Exact values explicitly reported for selected properties are distinguished from approximate readings of plotted trends. Percentage changes in Table 1 are calculated as $100 \times$ (filled value $-$ unfilled value)/unfilled value; the calculation does not provide statistical significance. Where the reported flexural-strength values are rounded, the resulting percentage is also treated as approximate.

3. RESULTS AND DISCUSSION

The tensile behavior is described in the four panels of Figure 1. They demonstrate the stress–strain diagrams of the unfilled reference, named P, and the three particle sizes. The order of their appearance corresponds to the original one. The applied loadings cannot be distinguished in the titles of the panels, and panels (a) and (b) depict the identical curves. Hence, they have been left unaltered without assigning any loads. The differences in the forms may suggest the differences in the peak stresses and deformations of the series but their quantitative comparison at the point of failure needs identification of panels, correct definitions of strains, and actual measurements.

There is an inconsistency in the tensile response between the stress–strain plots and the tensile strength diagram. The P curves in Figure 1 show the tensile strength around 50 MPa, whereas Figure 2 refers to the reference tensile strength of 29.5 MPa. In addition, the filled curves in Figure 1 peak under the displayed P curves while Figure 2 shows the higher tensile strengths in the filled samples. Thus, the inconsistency makes it impossible to establish a percentage increase in the tensile strength of the filled samples and make statements about increased or decreased ductility due to it.

The trends demonstrated in Figure 2 show the increase in the tensile strength from the unfilled samples to the maximum at 6 wt.% and the decrease at 8 wt.% for all three particle sizes. The 125 μm samples demonstrate the largest summarized value, 50.592 MPa, in contrast to the 29.504 MPa of the baseline. These values provide the increase of 71.5% in the tensile strength of the filled samples relative to the unfilled ones according to Table 1. This percentage is provisional because of the inconsistencies in the reference curves discussed above. The decrease at 8 wt.% implies that greater filler loading does not cause the monotonic increase in the tensile strength of the samples.

Young's modulus demonstrates the similar loading-dependent trend in Figure 3. It increases from 385 MPa of the unfilled polyester sample to the maximum of 674 MPa, which equals to the 75.1% increase. The maximum value is reached in the 125 μm samples at 6 wt.% and all three series decrease at 8 wt.%. Young's modulus is the stiffness measure in the strain range applied for its calculation; it is not a direct tensile strength or strain at failure measure. The lack of the modulus-fitting range and uncertainties precludes the assessment of sensitivity of the results to the calculation procedure.

The high values for the smallest nominal particles agree with the expected positive influence of interfacial area and stress transfer enhancement. In the case of particles of equal shape and density, reduction in the characteristic size leads to a rise in the specific surface area. As a consequence, reduction in the nominal size can lead to a rise in the number of particle-matrix contacts for the same mass of filler, assuming that the particles stay sufficiently well-dispersed. Nevertheless, it is impossible to draw conclusions about improved adhesion from tensile strength or modulus alone. Particle wetting, agglomeration, moisture content, and matrix curing can generate opposite influences, and none of these factors

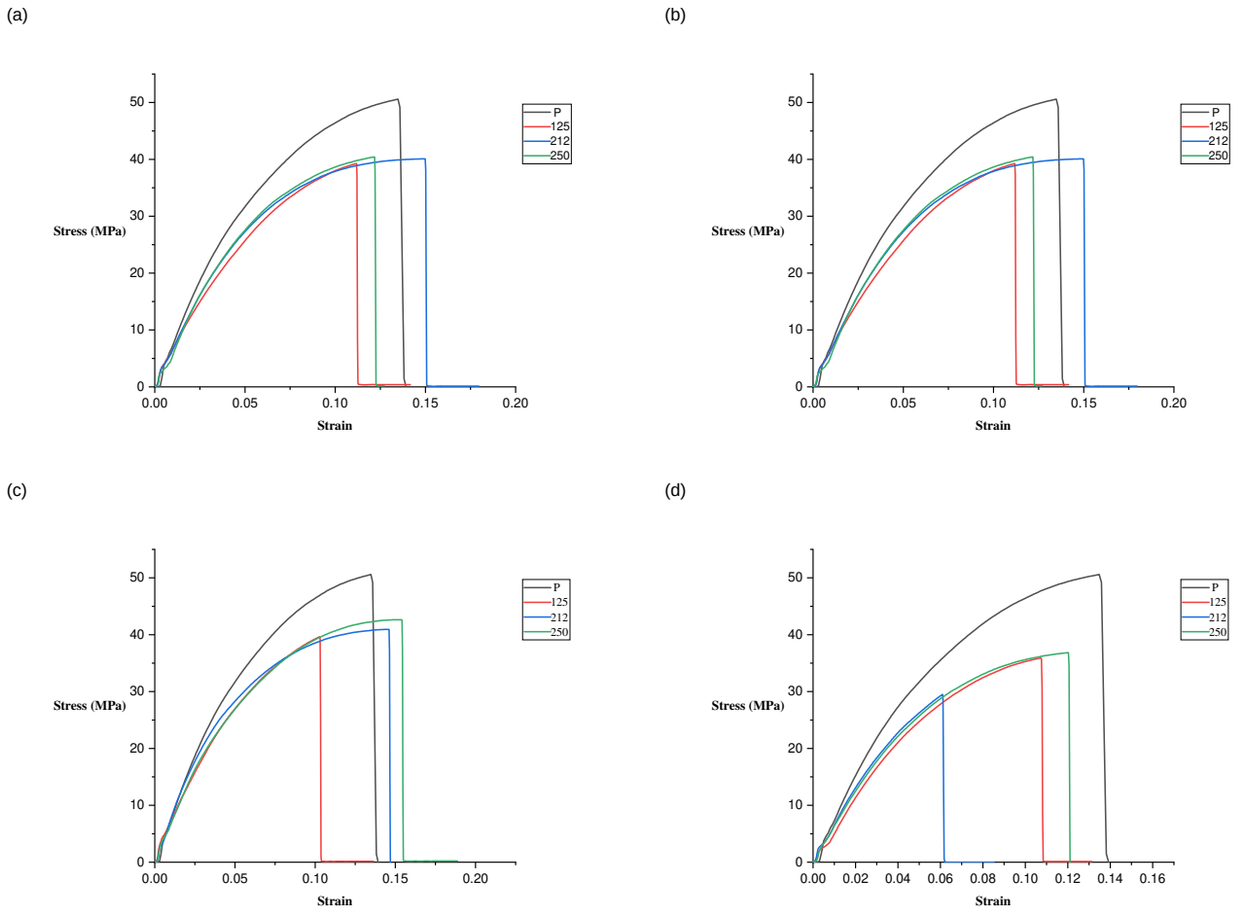


Figure 1. *Reported Tensile Stress–Strain Curves in the Original Panel Order*

was quantified independently in the present data set.

The decreases at 8 wt.% may result from worse dispersion, stress concentration, or porosity effects, but all these options remain unconfirmed hypotheses. An increased volume of particulate material may make mixing and particle wetting more difficult, especially when the viscosity of the resin becomes higher before casting. At the same time, the decreased strength can be associated with imperfections in specimens or batch-to-batch variations. The absence of fractography, porosity measurement, and additional experiments means that it is impossible to estimate the relative On the other hand, decreased strength may also result from specimen flaws or batch variation. Absence of fracture-surface images, void measurements, and additional tests precludes disentangling the contribution from each potential cause. The data thus demonstrate a non-monotonic response for the summary plots provided, but further measurement is necessary to determine the physical basis for the decrease in strength.

As shown in Figure 4, the flexural-strength data reveal that the particle-size ordering is loading-dependent. While the 250 μm series has the highest flexural strength at 2 and 4 wt.%, the 125 μm series has the highest strength at 6 and 8 wt.%. In both cases, each series achieves its greatest measured strength at the 6 wt.% loading level. The flexural-strength range reported suggests a rough increase from 29 to 50 MPa, corresponding to roughly 72%. The 125 μm series has the greatest flexural-strength response overall, but the strength difference is not observed at all loadings. There is a decline in each series at 8 wt.%. This section describes resistance to bending fracture in the specified test configuration, for which the stress is unknown.

Strength and ductility characterize the material in different ways and must be considered independently. An increase in strength is simply an increased level of stress at the end point of the test, while ductility refers to behavior before the material fails and needs to be measured by strain or displacement properly. Flexure will load a sample in tensile and compressive forces on different sections, which means the result will depend on such factors as surface conditions, thickness, span length, and loading mode. Due to the lack of information about these factors as well as flexure displacement data, the current results cannot prove any difference in ductility between the filled samples and unfilled polyester. However, a loading-dependent trend in strength may still be interpreted as a difference in stress level under bending.

However, the graph shown in Fig. 5 demonstrates a different trend compared to the two previous parameters. Hardness rises sharply from 0 wt.% to 4 wt.% for all size fractions. With further rise in load, the 125 μm sample set rises to reach

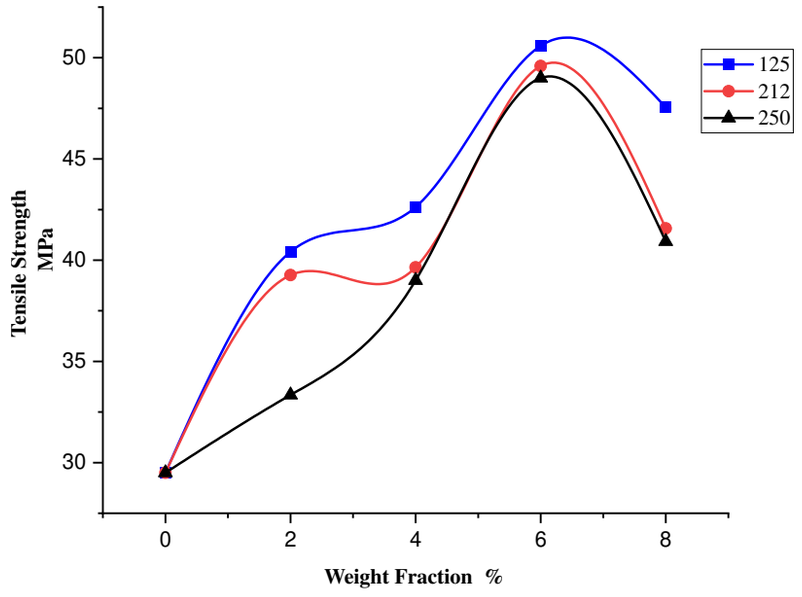


Figure 2. *Tensile Strength as a Function of Orange Peel Loading*

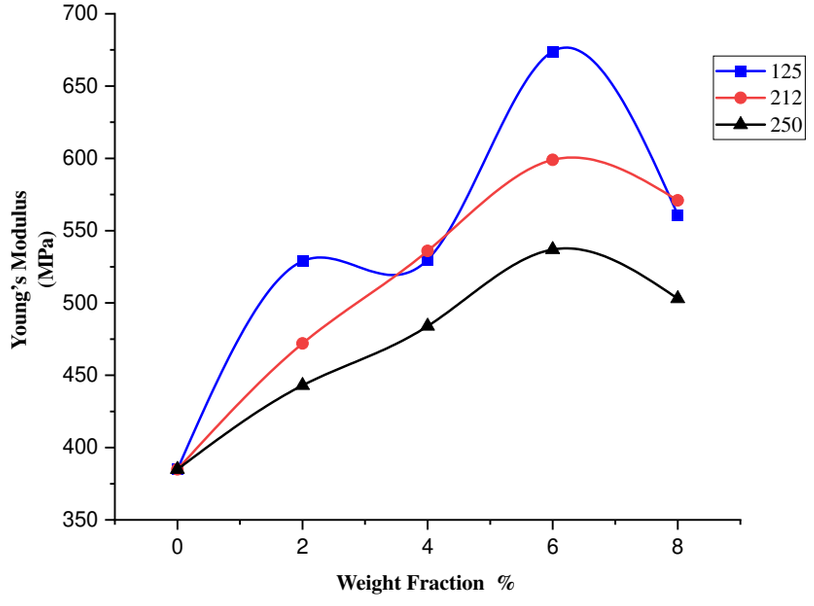


Figure 3. *Young's Modulus as a Function of Orange Peel Loading*

66.36 Shore D units at 8 wt.%, which is significantly higher compared to 36.8 for the unfilled polyester. This corresponds to the 80.3% increase arithmetically. However, this scale represents the value of indentation, and one should not assume that there is 80.3% increase in material strength.

However, increased resistance to indentation does not imply limited local deformability of the matrix in the presence of dispersed fillers. At the same time, the test measures the local property that does not have to be related to failure behavior under tensile and flexural loads. Thus, the material formulation can demonstrate the increased hardness value accompanied by decreased bulk strength. The divergence for the smallest particles between 6 and 8 wt.% confirms the idea that hardness cannot serve as an alternative to strength tests. The procedure requires surface preparation, thickness of the specimens, indentation dwelling time, as well as the number and intervals of the measurements to check if the differences in reported hardness values are reproducible results of the formulation effect.

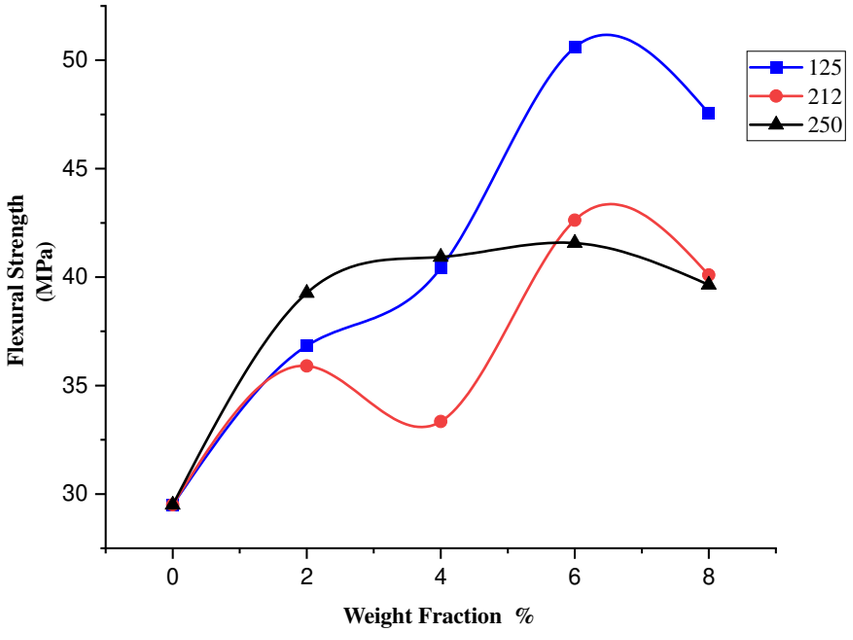


Figure 4. *Flexural Strength as a Function of Orange Peel Loading*

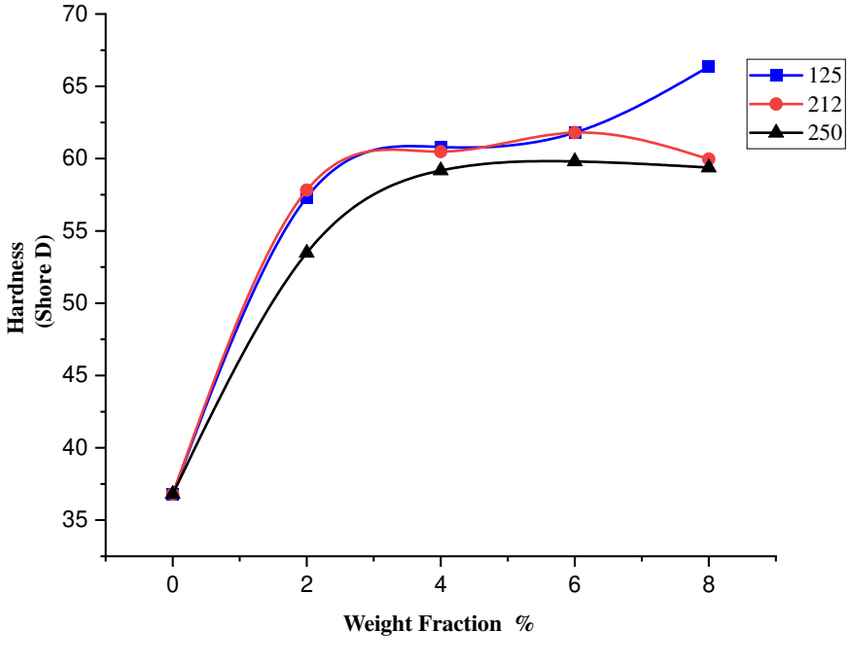


Figure 5. *Shore D Hardness as a Function of Orange Peel Loading*

Thermal conductivity values shown in Figure 6 increase with the increase in filler content. The 125 μm series provides the highest values among all filled compositions. Minimum and maximum values are 0.00109 and 0.03673 W/(m·K). Their ratio is about 33.7, which corresponds to the increase of 3269.7%. Maximum value relates to the smallest particles at 8 wt.%. Since the baseline is of great importance for relative changes, confirmation of the measurement method, units, sample thickness, contact resistance and calibration and calibration is particularly important before using these absolute values for material selection.

The probable reasons behind the effect of loading on the conductivity include variations in the particle spacing,

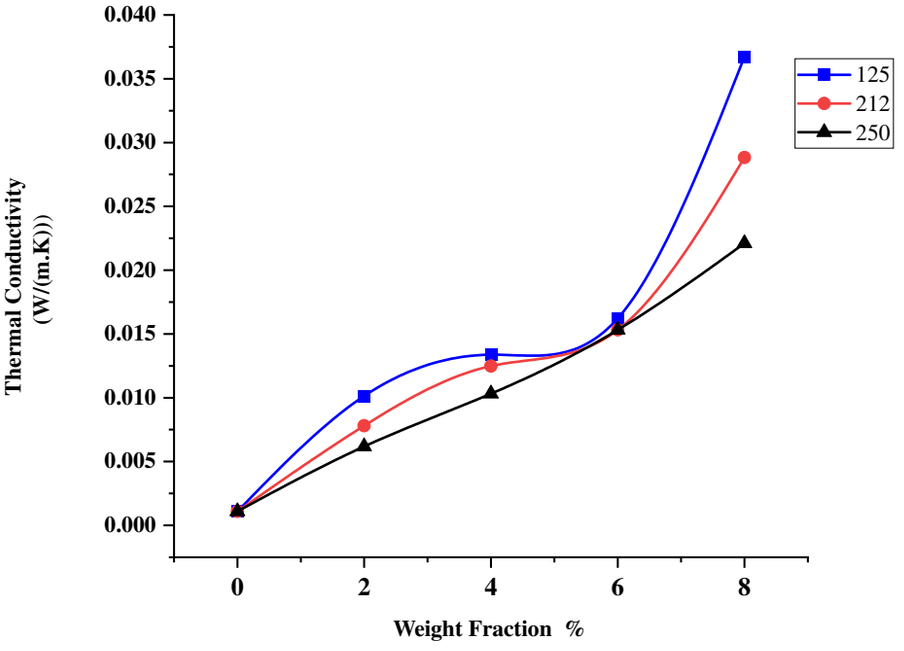


Figure 6. *Thermal Conductivity as a Function of Orange Peel Loading*

interfacial contact, and the heat transfer path continuity in the composites. Higher filling concentration can help in reducing the mean spacing between the particles, whereas the particle size and dispersion can affect the number and quality of contacts. The presence of voids can cause hindrance to conduction; however, its effects cannot be known without porosity or density data. In any case, there is no indication of a percolating network, better bonding, and void reduction from the conductivity graphs.

An increase in thermal conductivity means better conduction of heat, and this needs to be differentiated from increased thermal insulation. Under all other similar conditions, an increase in conductivity means higher heat conduction by that substance. Whether this is beneficial or not would depend upon the purpose it is meant to serve – insulation or heat dissipation. The observed trends might help in the assessment of a heat conducting composite, but cannot be taken as a measure of thermal stability, fire resistance, or high temperature capability. All of these would need different tests.

The selected numerical values obtained in the work, along with the associated arithmetic variations, are provided in Table 1. It is not to be assumed from the table that the maximum values are achieved within the same formulation. Tensile strength, modulus, and flexural strength show that 6 wt.% is the optimal concentration in the graph, while the maximum hardness and conductivity values were obtained at 8 wt.% for the 125 μm fraction. The proper choice of formulation should, thus, be based on the specific properties that have to be achieved.

The mechanical versus thermal difference plays an important role for choice of formulation. A rise in the level of loading from 6 to 8 wt.% in the 125 μm case series is associated with a reduction in tensile strength, tensile modulus, and flexural strength according to the summary graphs, while hardness and electrical conductivity are greater. Hence, an optimization of hardness will result in choosing a completely different composition from the one chosen by maximization of resistance to tensile or flexural breakage. Any discussion about filler content needs to begin with determining the property to be optimized and acceptable trade-offs before talking about preference of one composition to another.

Table 1. *Reported Property Endpoints and Arithmetic Changes*

Property	Unfilled	Reported Maximum	Change
Tensile Strength (MPa)	29.504	50.592	+71.5%[1]
Young's Modulus (MPa)	385	674	+75.1%
Flexural Strength (MPa)	≈29	≈50	≈72%
Hardness (Shore D)	36.8	66.36	+80.3%[2]
Conductivity (W/(m·K))	0.00109	0.03673	+3269.7%[3]

[1] Provisional: the unfilled stress–strain curves conflict with the tensile-strength summary. [2] Arithmetic change on the Shore D scale, not a strength ratio. [3] Reported units and measurement calibration require confirmation. Maxima occur at different loadings.

Orange peel as the filler provides one possible way of introducing a component derived from waste in polyester. This method alone is insufficient to prove that there will be lower costs of production, more efficient manufacturing process,

less harmful environmental impact, and safe performance in building and industry. There were no comparisons of costs, analysis of life cycle, tests for biodegradability, effects of prolonged moisture exposure, or evaluation of performance during use. These would need to be established as the goals of future investigation. First, it is needed to clarify the tensile strength reference and document the procedure.

4. CONCLUSION

Orange peel microparticles were added to polyester at three different sizes and four different percentages to evaluate the effects on specific properties. As seen in the plots, the 125 μm size provides relatively higher values for mechanical properties compared to other particle sizes. For example, tensile strength, modulus of elasticity, and flexural strength increase up to the maximum value around 6% and decrease at 8%, whereas hardness and thermal conductivity values increase continuously for the smallest size. The modulus value changes from 385 to 674 MPa, and hardness changes from 36.8 to 66.36 Shore D. However, the tensile-strength value change from 29.504 to 50.592 MPa is still provisional due to inconsistency of the control sample in the stress-strain plot.

The reported enhancement in conductivity from 0.00109 to 0.03673 W/(m·K) demonstrates increased conduction of heat and not enhanced insulation capacity. The findings as a whole provide an answer to the posed research question since they show that the use of increased amounts of orange peel causes various responses to the mechanical and thermal properties considered. While around 6 wt.% is optimal for the strength and modulus analysis, 8 wt.% seems optimal for hardness and conductivity of the smallest size of particles. Such findings need verification via consistent tensile test data, experimental procedures, and replicable measurements along with uncertainties.

Author Contributions

All authors contributed equally to this study and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this study.

Data Availability

The results presented in this article are reported in Figures 1–6 and Table 1. Individual specimen measurements, replicate-level data, and associated uncertainty estimates are not included in the article.

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Use of Artificial Intelligence

Artificial intelligence tools were used to assist with language editing and improvements to readability. The authors retain responsibility for the scientific content, interpretation of the results, and accuracy of the final manuscript.

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