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Sustainable Manufacturing Process Applied to Produce Waste Polymer-Polymer Matrix Composites

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Getting rid of plastic and rubber waste is one of the goals of achieving a sustainable lifestyle. Out-of-service tires and fuel and water tanks manufactured from polyvinyl chloride (PVC) are the most common waste that cities suffer from. This paper aims to investigate the effect of reinforced waste polymer particles on the polyester resin matrix when producing polymer matrix composite materials from waste tires and damaged plastic water tanks with different polymeric percentages. The polymer matrix composite could be used later in different applications, such as insulators and vibration dampers. The composite materials were evaluated by measuring the Shore D hardness, tensile strength, modulus of elasticity, and coefficient of thermal conductivity. The overall results showed hopeful behavior. Mixing a specific mixture of waste PVC and tires with polyester and hardener gives a higher tensile strength, modulus of elasticity, and Shore D hardness compared to each material when used separately. The thermal conductivity values increase with the mixing conditions between the materials. The thermal conductivity values can be reduced by using higher percentages of a mixture of waste tires and polyester or PVC and polyester. A 4.5% PVC, 4.5% tire and 91% (polyester and hardener) mixture can be recommended to improve tensile strength performance. A mix of 8.3% PVC, 8.3% tire, and 83.4% (polyester and hardener) can be recommended for high hardness.

Keywords: waste tire, waste PVC, polyester, polymer matrix, tensile strength, hardness.

Introduction

During the last decade, sustainability has become essential to many countries' environmental safety. Therefore, the legislation has become binding and restricting for many industries, leading to the closure of many factories for environmental considerations (Liu et al., 2000; McGrath et al., 2012). On the other hand, the polymer industry is considered one of the most dynamic manufacturing industries, as polymeric products have taken the place of many of their metal counterparts. The unique properties of polymers, such as their lightweight and high strength with the possibility of taking different colors and even being transparent, did not prevent the objections of environmental activists because of the difficulty of polymer degradation, which takes 4–5 centuries to analyze (Ober and Müllen, 2012). Out-of-service tires are considered a major problem with significant environmental impacts in addition to the economic cost, as waste rubber increases annually without any radical solutions (Abdel Kader et al., 2012).

On the other hand, another problem arises in many countries with hot or desert weather, where residents are forced to use a large water tank and a fuel tank often made of linear low-density polyethylene (LLDPE). Due to their prolonged exposure to harsh weather conditions, these tanks are out of service after a period. In such a case, the disposal of these damaged water tanks is vital (Shah et al., 2016; Gorrasi et al., 2002).

There are many classifications of rubber, including some in terms of applications and some in terms of saturation. The most used types are natural rubber, synthetic rubbers, nitrile-butadiene rubber, ethylene-propylene-diene monomer, polyurethane, and silicone rubber (Fazli and Rodrigue, 2020). Global rubber production has exceeded 25 million tons annually during the last five years. Around 50% of the rubber in tires is a polymeric material. Consequently, tire recycling is typically used to characterize rubber recycling (Medina et al., 2018). There are very abundant studies on the recycling of rubber and its use in many applications, such as insulators, dampers, and others. Amari et al. (1999) studied the burning of the end-of-life tire and found that burning rubber only returns 37% of the energy used to make the product. Shah et al. (2007) investigated the effect of calcium carbide catalysts on the distribution of rubber pyrolysis products, discovering that increasing the temperature in the presence of a calcium carbide catalyst increases the liquid fraction as total evolved gases while decreasing char yield. Afrin et al. (2021) identified many ways that can be used for out-of-service tires, such as reuse, reforming, ground tire rubber (GTR), regeneration of tire rubber, co-processing in cement production kilns, co-processing in thermoelectric power stations, pyrolysis of tire rubber, and landfill disposal. Roychand et al. (2020) published a comprehensive review on the use of rubber in conventional concrete to improve mechanical properties and insulation, and the results were encouraging.

Regarding the recycling of polymer tanks, Cardamone et al. (2022) got promising results using the dissolution/precipitation process during the supercritical extrusion process. They confirmed that large amounts of polypropylene and polyethylene could be recovered from fuel tanks and that other polymers that were not the main focus could also be treated. Graham et al. (2000) indicated that despite the contamination of the scrap plastic vehicle tanks, it is possible to recover about 27% of the high-density polyethylene (HDPE) using unique treatments. They indicated that recycled HDPE has similar mechanical properties to virgin ones. Istrate et al. (2021) studied the possible environmental impacts during the production of pipe-grade polyethylene (PE) resins using a blend of virgin and recycled HDPE. The recycled HDPE is collected from several sources, such as out-of-service tanks and industrial containers, detergency bottles, caps, and crates. They confirmed that the resulting product had lower environmental impacts and more recycled content.

Polyesters are made when polyols or glycols react with di-acids or their derivatives (anhydrides) to make condensation polymers (Dimian et al., 2019).

Polyester resins are unsaturated artificial resins having many good features, such as high resistance to severe weather conditions, especially high temperatures up to 80 °C, in addition to their resistance to chemicals and water, with a relatively low cost (Dimian et al., 2019).

More studies are required concerning the use of waste PVC and tires with polyester for a sustainable lifestyle. This study prepared three waste mixtures: waste tires and polyester, waste PVC and polyester, and waste tires plus PVC and polyester. The research looks into mechanical properties such as tensile strength, hardness, and plasticity, besides the study of thermal conductivity.

Experimental Work

Composite materials preparation

The grinding method directly affects the surface properties of the waste polymer particles. A heavy-duty bench grinder (RAJLAXMI, India) of 2800 rpm rotational speed and 1800 W power was used to grind the waste tire and out-of-service water tank, as shown in *Figs. 1a* and *1b*. The grinding particles were sorted to be around 1000 microns. Polyester resin with a hardener was used as a matrix, and waste polyvinyl chloride and waste tires were used as filler particles to produce particulate composite materials.

Two molds were fabricated in order to prepare the specimens. The first one is a square shape of 20 cm in length, and it was subdivided into four partitions, as shown in *Fig. 2a*. The second mold is rectangular with six partitions, each 30 cm long and 2.5 cm wide, as shown in *Fig. 2b*. The resulting specimens from the square mold were used in hardness and thermal conductivity measurements, while those from the rectangular mold were used in the tensile test.

Fig. 3 indicates several specimens that resulted from the square mold, where *Fig. 3a* indicates a pure specimen of polyester and hardener only, and *Fig. 3b* is a mixed specimen of polyester resin, hardener, waste tires, and waste PVC particles. *Fig. 3c* indicates the polyester, hardener, and waste PVC specimen, and *Fig. 3d* indicates several selected specimens.

Fig. 1. *Waste polymers grinding: (a) bench grinder, (b) waste tire grinding*

(a) *(b)*

Fig. 2. *Waste polymers molds: (a) square, (b) rectangular*

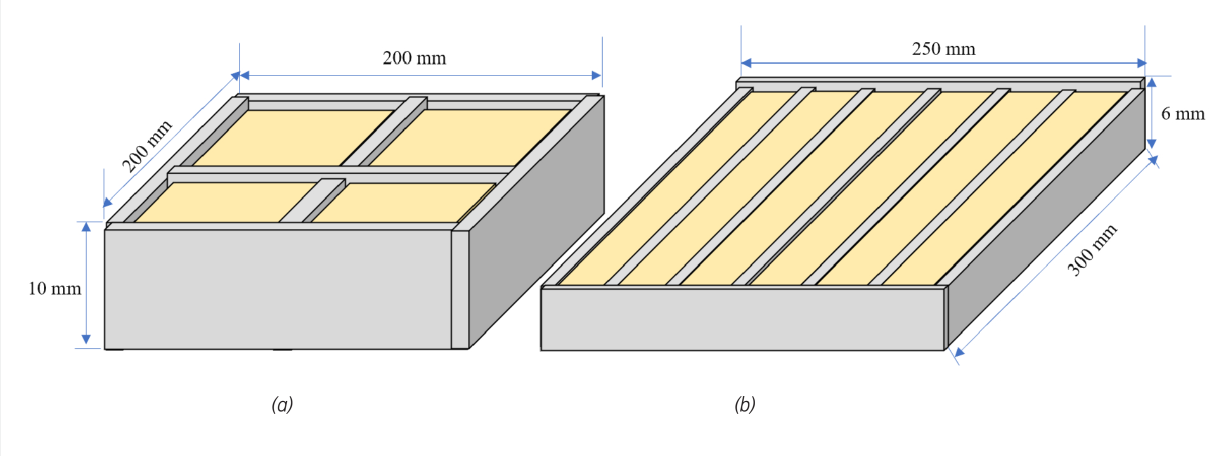


Fig. 3. *Squire mold specimens: (a) pure polyester and hardener, (b) polyester, waste tires and PVC, (c) polyester, hardener, waste PVC, and (d) different ratios specimens*

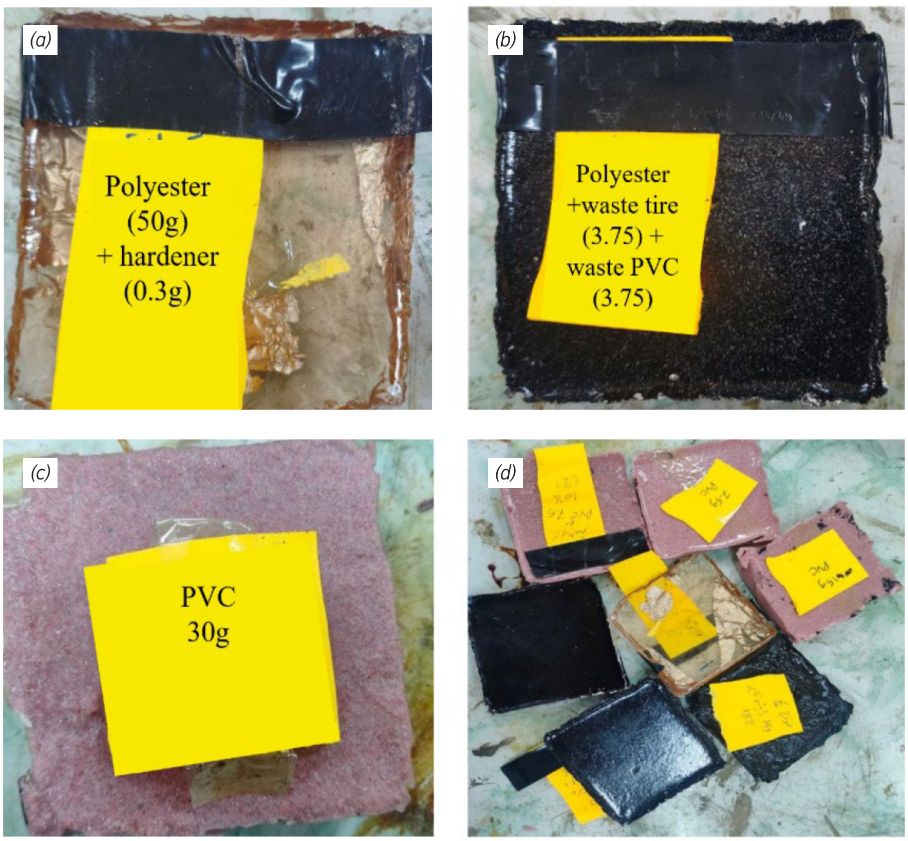


Fig. 4 indicates several specimens that resulted from the rectangular mold. *Fig. 4a* shows a mixed specimen of hardener, polyester, and waste tire, while in *Fig. 4b*, waste PVC was added. *Figs. 4c* and *4d* indicate mixed hardener, polyester, and waste PVC specimens at different ratios, while *Fig. 4e* indicates pure hardener and polyester specimens.

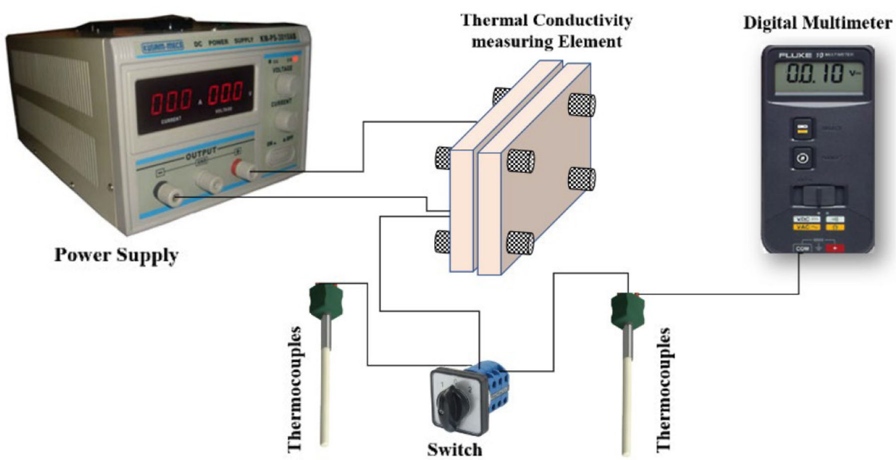
Sixteen specimens were prepared using different percentage ratios of the waste tire and PVC in a mixture of polyester and hardener. The first ten specimens were prepared using a square mold, and the weights of the polyester and hardener were 75 g and 0.45 g, respectively. These specimens measured hardness, theoretical modulus of elasticity, and thermal conductivity. The rectangular model was used to prepare six specimens for measuring tensile strength. The mixture weighed 50 g for the polyester and 0.3 g for the hardener.

Thermal conductivity measuring

Thermal conductivity was measured according to Lee's disk method and BS 4745 using locally fabricated apparatus, as shown in *Fig. 5*. In this apparatus, a power supply of 12V (Kusam-Meco, India) is used as a heat source with a digital multimeter (Fluke 10 series), where the selected waste plastic circle specimen is fixed between two disc brass plates.

Fig. 4. *Rectangular mold specimens: (a) pure polyester and hardener and waste tire, (b) polyester, hardener, waste tires and PVC, (c) and (d) polyester, hardener, waste PVC, and (e) pure polyester and hardener*

Fig. 5. *Thermal conductivity measuring apparatus*



Results and Discussion

As mentioned in *Table 1*, 16 specimens were tested. The first ten specimens (square shape) were used to investigate the shore D hardness, elasticity, and thermal conductivity. The rest six specimens were used to investigate the tensile strength.

Table 1. *Mixture percentage for each specimen*

Specimen	Weight %	Mold
1	100% (polyester + hardener)	Square shape
2	9% PVC + 91% (polyester + hardener)	
3	16.6% PVC + 83.4% (polyester + hardener)	
4	28.5% PVC + 71.5% (polyester + hardener)	
5	5% tire + 95% (polyester + hardener)	
6	9% tire + 91% (polyester + hardener)	
7	16.6% tire + 83.4% (polyester + hardener)	
8	4.5% PVC + 4.5% tire + 91% (polyester + hardener)	
9	6.85% PVC + 6.85% tire + 86.3% (polyester + hardener)	
10	8.3% PVC + 8.3% tire + 83.4% (polyester + hardener)	
11	100% (polyester + hardener)	Rectangular shape
12	9% PVC + 91% (polyester + hardener)	
13	16.6% PVC + 83.4% (polyester + hardener)	
14	28.5% PVC + 71.5% (polyester + hardener)	
15	9% tire + 91% (polyester + hardener)	
16	4.5% PVC + 4.5% tire + 91% (polyester + hardener)	

Shore D hardness and elasticity

After preparing the specimens and completing the curing, the square specimen was cut into discs with a diameter of 25 mm to measure the hardness of Shore D and the thermal conductivity, as shown in *Fig. 6*.

Fig. 6. *Specimens of the hardness and thermal conductivity measurement*

A handheld electronic tester measured Shore D hardness (PosiTector® SHD, Defelsko, USA) according to ASTM D2240. The modulus of elasticity was measured according to the correlation equation depending on the Shore D hardness, which was literate in previous studies as below (Qi et al., 2003). *Table 2* indicates the shore D hardness, elasticity, and thermal conductivity of the 1–10 specimens.

Table 2. *Hardness and elasticity of the specimens*

Specimen	Hardness Shore D	Elasticity (Pa)
1	29.4	1.110
2	22.6	0.828
3	21.6	0.790
4	18.6	0.680
5	28.6	1.070
6	26.0	0.960
7	18.6	0.680
8	28.0	1.050
9	28.3	1.060
10	28.6	1.070

$$\log_{10} E = 0.0235(D + 50) - 0.6403 \quad (1)$$

Where: (E) is Young's Modulus (in MPa) or modulus of elasticity; (D) is Shore D hardness.

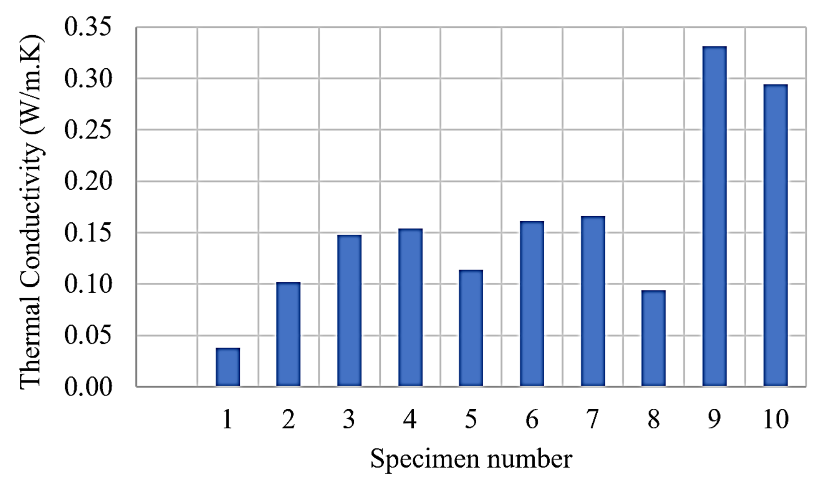
The resulting hardness values are around 18.6 to 29.4. The overall hardness behavior of specimens indicated that the hardness value decreased with an increase in the percentage of the waste PVC or waste tire in the mixture separately (specimens 2–4 and 6–7). Adding a mixture of waste PVC and waste tire as compared with previous specimens 2–7 led to improve hardness (specimens 8–9), which was also still lower than the hardness of the pure specimen of polyester and hardener (specimen 1), as shown in *Table 2*. The hardness of the specimens that included the waste tire is harder than that of the specimens that included waste PVC such specimen 6 vs specimen 2 since rubber tires can withstand significant pressure because of their complex properties (Faizah et al., 2019). Because the modulus of elasticity is directly proportional to the Shore D hardness, the behavior of specimens concerning the modulus of elasticity will be similar to their behavior in terms of Shore D hardness. The lower hardness of the resulting rubber indicates more tendency to the elasticity.

Moreover, *Table 2* illustrates the findings, which indicate a noticeable decrease in hardness with increasing additive %, either waste tire or waste PVC, resulting from increased chain mobility of the polymer matrix, which is highly important for flexibility. However, the hardness did not change much when wastes were added to the polymer matrix. The effect was because waste particles had a negligible effect on hardness and their compatibility or stiffness increased.

Thermal conductivity

The thermal conductivity was measured according to Lee's disk method and BS 4745. *Fig. 7* shows the resulting thermal conductivity in specimens that used waste PVC or waste tires separately with polyester and hardener, as well as when the different ratios were mixed. The thermal conductivity shows a linear, incremental behavior with increasing mixing ratios. This behavior is similar to some previous studies, especially concerning waste tires (Yang et al., 2022). The overall thermal conductivity values are still limited and within the accepted ranges for applications such as insulation. The thermal conductivity of specimens decreased with increasing percentages of additive, whether waste tire or PVC, because of the specimens' high thermal insulation properties, as shown in *Fig. 7*. However, the thermal conductivity was only slightly reduced after adding both wastes to the polymer matrix since neither waste affected the insulating properties.

Fig. 7. *Thermal conductivity of the specimens*



Tensile strength

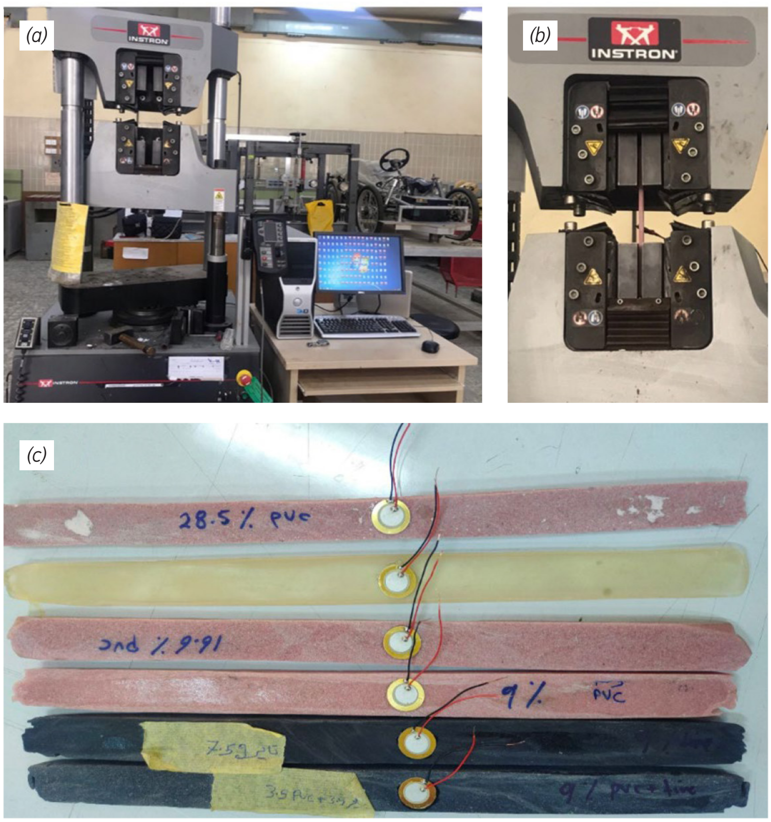
The universal tensile machine (Instron, USA) was used for getting the tensile strength, where the specimens were prepared using rectangular mold according to ASTM D 3039. The specimens' dimensions were 300 x 20 x 8 mm in length, width and thickness, respectively. A linear variable differential transformer (LVDT) sensor fixed by glue on specimens was used as an elongation indicator during the tensile test, as shown in *Fig. 8*.

After tensile testing of all six specimens and as shown in *Table 3*, specimen No. 11 (polyester and hardener only) showed brittle behavior and broke after only a few seconds. Mixing quantities of waste PVC with polyester and the hardener has improved the material's tensile strength (specimens 12–14). The continuation of increasing waste PVC gives opposite results, and this behavior is similar to several previous studies (Al-Mosawi et al., 2019). Regarding adding waste tire ratios, the tensile strength improved more than in the previous cases (specimen 15).

Table 3. *Tensile strength of the specimens*

Specimen	Weight ratios (%)	Tensile strength (MPa)
11	100% (polyester + hardener)	2.00
12	9% PVC + 91% (polyester + hardener)	27.0
13	16.6% PVC + 83.4% (polyester + hardener)	24.0
14	28.5% PVC + 71.5% (polyester + hardener)	23.0
15	9% tire + 91% (polyester + hardener)	29.5
16	4.5% PVC + 4.5% tire + 91% (polyester + hardener)	30.4

Fig. 8. *Tensile test preparation: (a) tensile test machine, (b) specimen fixation, (c) elongation sensor fixation*



Furthermore, adding a waste tire and PVC mixture to the polyester and hardener gave the best tensile strength at the break (sample 16).

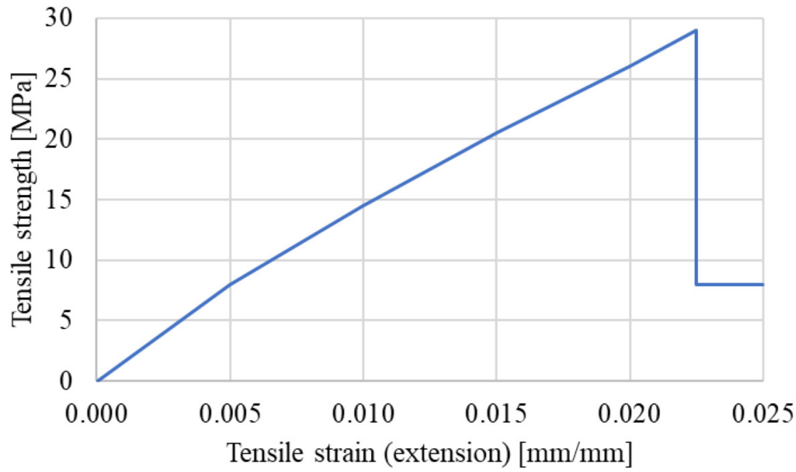
In general, adding waste PVC or waste tire to polyester and hardener separately or together gave the samples' behavior in the tensile test behavior similar to the behavior of the plastic material, where the stress-strain curve gradually increased until the fracture occurred at the maximum value of the tensile strength. Compared to some previous studies, the ratios chosen for this study gave higher values for tensile strength than those found in those studies (Formela, 2022; Laoutid et al., 2021).

The fracture locations of the specimens differed during the tensile test. However, most of the samples failed in the center of the specimens or near the center, except for specimen No. 11, which consisted of polyester and hardener only, where it failed immediately after applying very little force and showed brittle behavior due to the rigidity and glassy nature of virgin specimens as shown in *Fig. 9*. Further, *Fig. 10* refers to their behavior under stress, revealing brittle specimens. However, the addition of waste polymer enhanced the composite's ductility, affecting all specimens' strength.

As an overall discussion between the experimental sets and the corresponding results, the maximum hardness and minimum thermal conductivity were achieved for the pure specimen (No. 1), where no additive of waste PVC or tire parts was added. For the first specimens' group (2–4), where only waste PVC parts were added and increased gradually, the resulting hardness decreased, while reverse thermal conductivity behavior occurred. For the second group of specimens (4–7), where only waste tire parts were added and increased gradually, similar behavior to the previous case occurred for both hardness and thermal conductivity. When the mixing process occurred in specimens (8–10), there was a significant improvement in hardness and thermal conductivity. Regarding the tensile test, the samples with limited mixing of waste PVC and tire give better performance.

Fig. 9. *Fracture location of specimens after tensile testing*

Fig. 10. *Stress-strain curve for virgin specimen number 15*



Conclusions

Sustainability is an essential factor in the outlook for the industry. Sustainability depends on several aspects, the most important of which is the possibility of recycling or reusing products. In this study, two types of waste were used, namely waste tires and waste PVC, to study tensile stress, hardness, modulus of elasticity, and thermal conductivity to produce materials that can be used later in other applications such as insulation, vibrations, and the like. The study proved the following:

1. Mixing a specific mixture of waste PVC and tires with polyester and hardener can give a composite material high tensile strength compared to each material when used separately.
2. The thermal conductivity values increase with the mixing conditions between the materials, and the thermal conductivity values can be reduced by using higher percentages of a mixture of waste tires and polyester or a mixture of waste PVC and polyester.
3. Mixing waste PVC and waste tires with polyester led to a clear improvement in the hardness values and made the resulting material more flexible by increasing the modulus of elasticity.
4. A 4.5% PVC, 4.5% tire, and 91% (polyester and hardener) mixture can be recommended to improve tensile strength performance. A mix of 8.3% PVC, 8.3% tire, and 83.4% (polyester and hardener) can be recommended for high hardness.

References

Abdel Kader, M. M., Abdel-wehab, S. M., Helal, M. A., and Hassan, H. H. (2012). Evaluation of thermal insulation and mechanical properties of waste rubber/natural rubber composite. HBRC Journal, 8(1). https://doi.org/10.1016/j.hbrcj.2011.11.001

Afrin, H., Huda, N., and Abbasi, R. (2021). Study on End-of-Life Tires (ELTs) Recycling Strategy and Applications. IOP Conference Series: Materials Science and Engineering, 1200(1). https://doi.org/10.1088/1757-899X/1200/1/012009

Al-Mosawi, A. I., Al-Maamor, M. H., Marossy, K., Yasser, H. A., and Abdulsada, S. A. (2019). Mechanical Properties of Acrylonitrile-Butadiene Rubber (NBR)/Poly (Vinyl Chloride) Resin Binary Blend. OALib, 06(12), 1-7. https://doi.org/10.4236/oalib.1105956

Amari, T., Themelis, N. J., and Wernick, I. K. (1999). Resource recovery from used rubber tires. Resources Policy, 25(3). https://doi.org/10.1016/S0301-4207(99)00025-2

Cardamone, G. F., Ardolino, F., and Arena, U. (2022). Can plastics from end-of-life vehicles be managed in a sustainable way? Sustainable Production and Consumption, 29. https://doi.org/10.1016/j.spc.2021.09.025

Dimian, A. C., Bildea, C. S., and Kiss, A. A. (2019). Applications in design and simulation of sustainable chemical processes. In Applications in Design and Simulation of Sustainable Chemical Processes. https://doi.org/10.1016/C2015-0-06856-3

Faizah, R., Priyosulistyo, H., and Aminullah, A. (2019). The Properties of Waste Rubber Tires in Increasing the Damping of Masonry Wall Structure. IOP Conference Series: Materials Science and Engineering, 650(1). https://doi.org/10.1088/1757-899X/650/1/012041

Fazli, A., and Rodrigue, D. (2020). Waste rubber recycling: A review on the evolution and properties of thermoplastic elastomers. In Materials (Vol. 13, Issue 3). https://doi.org/10.3390/ma13030782

Formela, K. (2022). Waste tire rubber-based materials: Processing, performance properties and development strategies. Advanced Industrial and Engineering Polymer Research, 5(4), 234-247. https://doi.org/10.1016/j.aiepr.2022.06.003

Gorrasi, G., Maio, L. di, Vittoria, V., and Acierno, D. (2002). Recycling polyethylene from automotive fuel tanks. Journal of Applied Polymer Science, 86(2). https://doi.org/10.1002/app.10967

Graham, P. M., Yernaux, J. M., Dupont, S., and Decannière, J. (2000). Post-consumer plastic fuel tank recycling. SAE Technical Papers. https://doi.org/10.4271/2000-01-1093

Istrate, I. R., Juan, R., Martin-Gamboa, M., Domínguez, C., García-Muñoz, R. A., and Dufour, J. (2021). Environmental life cycle assessment of the incorporation of recycled high-density polyethylene to polyethylene pipe grade resins. Journal of Cleaner Production, 319. https://doi.org/10.1016/j.jclepro.2021.128580

Laoutid, F., Lafqir, S., Toncheva, A., and Dubois, P. (2021). Valorization of Recycled Tire Rubber for 3D Printing of ABS- and TPO-Based Composites. Materials, 14(19), 5889. https://doi.org/10.3390/ma14195889

Liu, H. S., Mead, J. L., and Stacer, R. G. (2000). Environmental effects of recycled rubber in light-fill applications. In Rubber Chemistry and Technology (Vol. 73, Issue 3). https://doi.org/10.5254/1.3547605

McGrath, J. E., Hickner, M. A., and Höfer, R. (2012). Introduction: Polymers for a Sustainable Environment and Green Energy. In Polymer Science: A Comprehensive Reference, 10 Volume Set (Vol. 10). https://doi.org/10.1016/B978-0-444-53349-4.00301-0

Medina, N. F., Garcia, R., Hajirasouliha, I., Pilakoutas, K., Guadagnini, M., and Raffoul, S. (2018). Composites with recycled rubber aggregates: Properties and opportunities in construction. In Construction and Building Materials (Vol. 188). https://doi.org/10.1016/j.conbuildmat.2018.08.069

Ober, C. K., and Müllen, K. (2012). Introduction - Applications of Polymers. In Polymer Science: A Comprehensive Reference, 10 Volume Set (Vol. 8). https://doi.org/10.1016/B978-0-444-53349-4.00199-0

Qi, H. J., Joyce, K., and Boyce, M. C. (2003). Durometer hardness and the stress-strain behavior of elastomeric materials. Rubber Chemistry and Technology, 76(2). https://doi.org/10.5254/1.3547752

Roychand, R., Gravina, R. J., Zhuge, Y., Ma, X., Youssf, O., and Mills, J. E. (2020). A comprehensive review on the mechanical properties of waste tire rubber concrete. In Construction and Building Materials (Vol. 237). https://doi.org/10.1016/j.conbuildmat.2019.117651

Shah, J., Jan, M. R., and Mabood, F. (2007). Catalytic conversion of waste tyres into valuable hydrocarbons. Journal of Polymers and the Environment, 15(3). https://doi.org/10.1007/s10924-007-0062-7

Shah, K. N., Varandani, N. S., and Panchani, M. (2016). Life Cycle Assessment of Household Water Tanks-A Study of LLDPE, Mild Steel and RCC Tanks. Journal of Environmental Protection, 07(05). https://doi.org/10.4236/jep.2016.75068

Yang, Y.-L., Zhang, T., Reddy, K. R., Li, J.-S., and Liu, S. (2022). Thermal conductivity of scrap tire rubber-sand composite as insulating material: Experimental investigation and predictive modeling. Construction and Building Materials, 332, 127387. https://doi.org/10.1016/j.conbuildmat.2022.127387