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Solvolysis-Based Process for Development of an Anti-Shock Composite Material from Post-Consumer Polystyrene (PS) and Urban Wastes

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Abstract

This study focused on recovering plastic waste from different landfill sites in Lubumbashi. The primary method used to create the shock-resistant composite material used in the military to make bulletproof waistcoats and vehicle shielding, among other personal and group protective equipment, was solvolysis. The aim of this research was to develop and investigate the possibility of using recycled plastics to create impact-resistant composite materials that resembled those found in bulletproof waistcoats. This was accomplished by recycling plastic waste, such as bottles made of polystyrene (PS), by solvolysis to achieve high mechanical properties and minimize any potential pollution risks. Similar strength and lightweight characteristics to those of conventional materials can be achieved through material creation. Examining the product that was left behind after dissolving, mechanical testing revealed that recycled polystyrene possessed exceptional mechanical qualities, such as a 65% increase in Rockwell hardness, a tensile value of 400 MPa, and a 4.5 MPa elongation. This solution is a mixture of an alkaline solution saturated in [KOH] liq, a semi-polar organic solvent [$C_{10}H_{16}$] liq, and Cu^{2+} sulphate [$CuSO_4$].

Keywords

Recycling, Solvolysis, Plastic, Composite Material, Polystyrene (PS)

1. Introduction

Given its impact on the economy and ecology, the trash recycling issue is one of the most difficult subjects facing society today [1]. Polymers, or "long chains of monomers", are another name for plastics. These subunits are joined to one another to form a polymer. Polymers can come from natural sources, such cellulose, which is the fundamental component of plant cell walls and aids in cell function adaptation [2] [3]. The extensive range of industrial and home uses for polymer materials has made them indispensable in today's world [4]. Recycling waste is essential for a sustainable ecosystem, particularly plastics, which are mostly made from non-renewable resources like fossil fuels [1]. Furthermore, plastic is more difficult for microorganisms to break down than other types of biomasses, like lignin and chitin, which pollutes the environment [5]. Likewise, there is no guarantee that substituting plastic will benefit the environment because other packaging materials, including glass or metal containers, are heavier and produce more CO_2 emissions during transportation [6] [7]. Plastic waste is a widespread environmental issue, because plastics are used in many aspects of our society. Materials made from polymers by chemical processes with chemicals and additives are what they are [8]. Thermoplastics (polyethylene PE, low-density polyethylene LDPE, high-density polyethylene HDPE, polyethylene terephthalate PET, polypropylene PP, polyvinyl chloride PVC, and polystyrene PS) and thermosets (phenol-formaldehyde PF, unsaturated polyesters UP, polyurethane PU, and epoxy EP) are the two categories into which they fall [1]. Plastic garbage is therefore typically disposed of in the environment by being deposited in landfills [9] [10]. Meanwhile, plastic waste is typically recycled and burned to create energy, allowing for the regeneration and utilization of a large amount of energy in various ways [11].

One of the most popular polymers is polystyrene (PS), which is perfect for lightweight packaging, filling, and insulation because of its favorable qualities, which include colorlessness, lack of flexibility, and plastic hardness. It is especially useful for building insulation, refrigeration boxes, and catering boxes. Furthermore, it is a material with significant shock-absorbing qualities [12]-[14]. Its mechanical capacities would be greatly increased by additional treatment, such as chemical recycling and reforming into a composite, which would expand its range of safety applications [15].

There are four key categories of plastic waste recycling methods: primary recycling, secondary mechanical recycling, tertiary chemical recycling, and energy recovery [5]. The best recycling technique in every way is primary recycling, which is the reuse of production waste in the creation of plastic products. Raw materials from mechanical processing techniques are utilized to create new plastic goods [16]. However, when it comes to highly mixed and polluted plastic trash, mechanical recycling procedures (secondary recycling) have significant limitations. In this instance, chemical recycling procedures can assist in bridging the cycle's gaps [17]-[19]. The chemical recycling of plastics is an industrial process that involves breaking down long-chain organic macromolecules into short-chain organic molecules, monomers, or their constituent parts, then using at least some of the breakdown products to create new plastics. Numerous processes, including hydrolysis, hydrocracking, pyrolysis, gasification, catalytic cracking, and solvolysis, can be differentiated based on the chemical principle [20] [21].

Solvolysis is a chemical process that can break down polymers like polystyrene (PS) into their monomers or other useful chemicals. By using post-consumer PS and urban waste, this process can help in recycling and creating new materials, which is great for sustainability. An anti-shock composite material would be designed to absorb and dissipate energy, making it useful in various applications like packaging, automotive parts, and protective gear.

In this work, we explore how combining recycled PS with other urban waste materials could enhance the properties of the composite, such as its strength, durability, and shock-absorbing capabilities.

2. Materials and Methods

The sampling location is situated in the Haut-Katanga province's Lubumbashi commune, Mampala district, and city. The local populace has struggled to manage rubbish in this area of the city for over ten years. A green area has been transformed into a public waste dump, and because of poor site management and upkeep, some hygiene services have turned it into a cemetery. As illustrated in **Figure 1**, the facility is in appalling condition and has occasionally turned into a source of pollution.

Figure 1. Discharge of plastic waste on Kyungu Wa Kumwanza boulevard (ex Katuba, stop 5 pailottes).

2.1. Sampling

The method used for sampling was called non-probabilistic sampling, sometimes referred to as the empirical or rational choice method. It involves a non-random selection process based on subjective criteria that vary depending on the interviewers' choice, feasibility criteria, and similarity to the target. The large amounts of plastics found in landfills serves as justification for the technique's selection. Three sampling points are part of the sampling plan. The following equipment is required for this operation:

2.2. Raw Materials

The raw materials used in this work was organics totally such as PS waste that are a plastic polymer, organic solvent and Spider silk, which is a polymer-based fibre.

2.3. Polystyrene Preparation

When the material to be processed requires polystyrene that is not contaminated by food remnants (soup, food residues) and is free of coloring and labels, this landfill garbage must be prepared as follows:

- ✓ **Collection and sorting**: Mixed polystyrene garbage was collected and separated to keep only the polystyrene in the form of packaging (single-use packaging), given its abundance.
- ✓ **Washing**: A washing with water was adequate to release the contaminants on the surface of our raw material, such as the surrounding garbage, labels, stickers, soup, etc.
- ✓ **Drying**: The latter was dried in the sun to remove any remaining water after washing.
- ✓ **Shredding**: polystyrene packaging reduces its size (granulometry ≤ 1 cm) and improves its dissolving kinetics in solvents.

  Figure 2 shows a flowsheet preparation of the raw material (polystyrene).

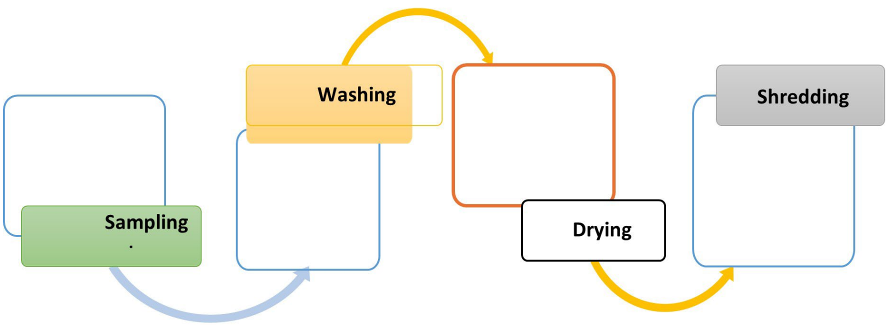

Figure 2. Shows a flowsheet for preparing the raw material (polystyrene).

2.4. Solvent Preparation

The d-limonene-based solvent was made up of 2/4 limonene, 1/4 copper II sulphate, and 1/4 alkaline compound. This combination was created with the goal of increasing the solubilising power of the reagent used to dissolve all polystyrene and other types of plastic. Limonene is a semi-polar organic solvent with the qualities listed in Table 1 below.

Table 1. Properties of d-limonene solvent

Aspect	Water clarity
Purity (%)	95
Refractive index (à 25˚C)	±1.4704 to ± 1.4711
Specific weight	0.839 to 0.845

The choice of d-limonene was driven by the fact that it is more than 30% natural, non-toxic (when used as directed and with proper safeguards), and biodegradable, as opposed to toluene, acetone, or sulfuric acid. Furthermore, it is not combustible at room temperature and emits no harmful fumes; it is also more stable and soluble than other solvents. Table 2 shows the characteristics of the copper II sulphate used to prepare the solvent.

Table 2. Characteristics of copper II sulphate.

Aspect	Blue
Solubility in water at 100˚C	2033 g/L
Absorption spectrum ƛ	800 nm
melting point	110˚C

Following processing, the resulting solvent has a dark blue hue, as seen in Figure 3 bellow.

Figure 3. d-limonene based solvent.

2.5. Solvolysis of Polystyrene

The basis of solvolysis (dissolution) is that the solute forms low-energy bonds with the solvent, has double bonds in its structure, and protons in positions 2, 3, 8, and 9, as shown in Figure 4 below.

The resulting d-limonene-based solvent was poured into a reaction vessel, as seen in Figure 5.

In contact with the polystyrene at room temperature with a modest agitation of 1 rpm, the dissolving rate of the polystyrene is satisfactory in a quick and spontaneous reaction as illustrated in Figure 6, 20 seconds after the polystyrene encounters the solution. It is worth noting that the solvent dissolves different types of thermoplastic polymers, as shown in **Figure 6**.

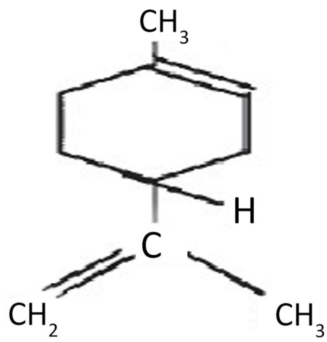

Figure 4. d-limonene molecule.

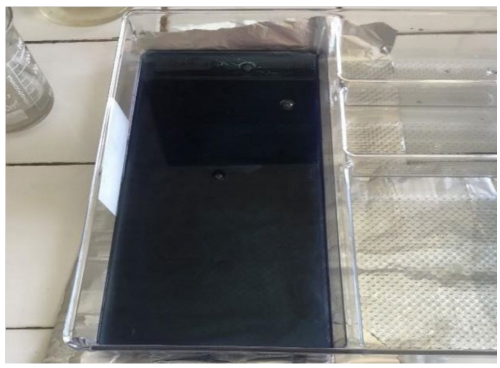

Figure 5. Solvent prepared in the laboratory.

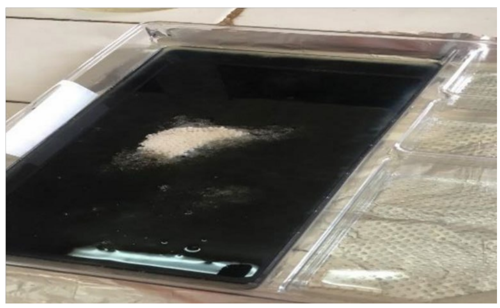

Figure 6. Illustration of PS dissolution in d-limonene after 20 s.

Following the dissolution of polystyrene and other thermoplastic polymers, filtering was used to separate the solute (recycled PS) from the solvent. Polystyrene was then dissolved and reduced to one-twentieth of its original volume. The recycled polystyrene was found in the form of thick granules.

Because d-limonene acts as an antioxidant, the recovered solvent retains its properties throughout the process and can be reused. It stops electrons from leaving the atoms as the PS dissolves. As a result, the molecular weights remain constant, and the material retains its properties. Most EPS recycling processes known to date are carried out at high temperatures, which causes degradation of the molecules, resulting in a recycled material with weaker mechanical properties due to oxidation.

It should be observed that the content of the solvent had virtually no impact on the composition of the solute, i.e. polystyrene. The operating settings are provider in Table 3.

Table 3. Operating conditions.

Volume of solvent	100 ml
Stirring speed	1 rpm
pH	6.6 to 7.1
Temperature of media	22˚C

Figure 7 illustrates the polystyrene dissolution process.

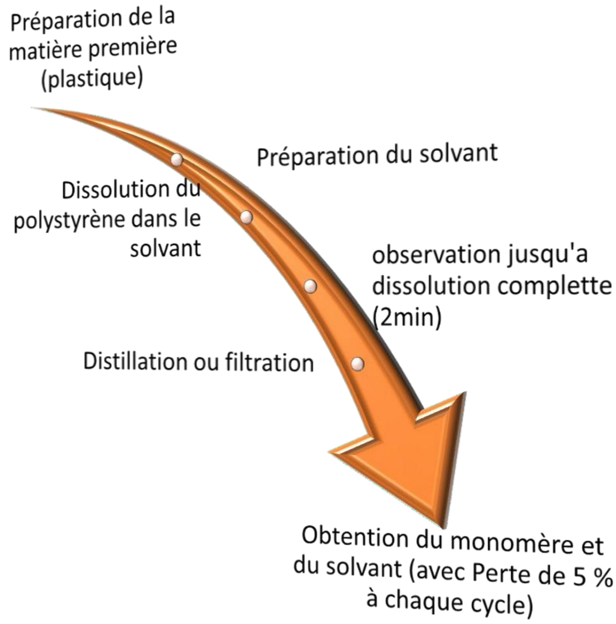

Figure 7. Diagram of obtaining monomer by dissolution.

At this point, it is crucial to note that the recycled polymer contains the same proportion of solutes by weight after the solvent has been completely evaporated as it did before treatment. This enables us to classify the approach as lossless. It should be mentioned that the re-polymerization mechanism has not been fully understood due to challenges in witnessing the reactions in progress. As a result, the material obtained is suitable for usage as a matrix in our composite material. The procedure will be followed in accordance with a predetermined standard, taking into consideration the availability of laboratory equipment and the resources at our disposal.

It should also be emphasized that the recycled PS was moulded into sheets, and the reinforcement, spider silk woven using the SIC-SIC process, was layered on top to create a sandwich structure.

3. Results and Discussion

3.1. Drill Penetration Test

The penetration test is a laboratory procedure designed for manipulation. The goal is to determine the bullet-proof waistcoat's capacity to withstand penetration by a sharp object, or in this case, a high-velocity projectile, as it moves helical. In this method, we can assess the level of protection it can provide against stabbing weapons and bullets, ensuring the wearer's safety.

3.2. Fibre Elongation on Impact

Testing fibre elongation upon impact or breakage: Micro-fractures are the primary means by which composite materials absorb impact energy. This means that energy absorption is heavily influenced by the breaking tension of the fibres. When the fibres break, no additional energy is absorbed. One could expect the energy to be absorbed by plastic deformation or fibre geometry. A piercing machine was used to assess fibre elongation on impact, and the results are shown in Table 4.

Table 4. Data relating to the drill used for the test.

Energy per second	1000 J/5 sec (200 J/s)
Speed of rotation (rpm)	2800
Penetration (cm/min)	4880
Drilling tip diameter (cm)	1.3

The obtained results were compared to existing values to draw conclusions based on the objectives pursued by our work, namely the feasibility study and evaluation of the performance provided by a composite material for ballistic use who's ceramic and/or metal inserts will be replaced by a recycled polystyrene insert and whose reinforcing material is hand-woven spider silk fibre. Table 5 illustrates the physical properties of polystyrene-based materials.

Table 5. The physical parameters of polystyrene-based materials.

Parameters	Method	units	Value
Coefficient of linear expansion		Mm/˚C	9.10 E − 5
Rockwell hardness	ISO 62	%	0.4 − 0.7
Flexural modulus of elasticity	ISO 178	MPa	2100
Density	ISO 1183	$g.Cm^{-3}$	1.04
Elongation at break	ISO 527 − 2	MPa	20

3.2.1. Elasticity Modulus

The modulus of elasticity values is provided in Table 6.

Table 6. Elasticity modulus values (GPa).

MATERIAL	ELASTICITY VALUE (GPa)
Polyethylene	
Carbon composite	420
Glass composite	80
Polystyrene	-
Nylon	-
Aluminium alloy	75
Structural steel	210

When we compare polystyrene supplied on the market to other materials such as carbon or glass fibre composites or steel, we see an obvious difference: its Young's modulus is lower than that of its neighbours. Despite these major variances, polystyrene remains the most popular bumper material.

3.2.2. Recycled Polystyrene

Laboratory study on materials based on recycled polystyrene produces the following results in Figure 8 below.

Figure 8. Appearance of polystyrene after molding seen from above.

The colour of the polymer changed when it was mixed with the dye, and this occurred when our materials set. The setting mechanism involves trapping a lower amount of solvent, air, and other ambient vapours, as evidenced by the visual presence of air bubbles in the test tubes.

Table 7 below shows the characteristics of molded polystyrene plates.

Table 7. Characteristics of polystyrene molded plates.

Number of plates	Sheet size (cm)	Weight (g)	Thickness (cm)	Aspect
2 for the prototype (1 front/1 rear)	40*40	500*2	3	Black
3 for testing	8*4	75	-	Black

3.2.3. Reinforcement: Silk Fibre

Composite materials rarely contain the reinforcement utilized. Materials experts refer to it as the material of the future. Simply put, it's silk (spider) fibre. Table 8 below describes the format used in our composite material.

Table 8. Characteristics of the layers of silk woven by hand.

No. of silk mats	Weight by mats (g)	Area by mats (cm^2)	Shape
8	250	40*40	Rectangle
8	50	8*4	Rectangle
Weaving/armoring		2D woven SIC-SIC	

Figure 9 illustrates the layers of hand—woven silk.

Figure 9. Layers of hand—woven silk.

Bullet-proof waistcoats do not immediately stop bullets; instead, they absorb their kinetic energy and distribute it throughout the waistcoat's full surface. To accomplish this, the material must have closely intertwined fibres. Individual fibres are typically twisted to increase density and thickness at each location. To increase rigidity, the material is covered with resin and clamped between two layers of plastic film. A person wearing a bullet-proof waistcoat will always feel the energy of a bullet's impact across their entire body rather than just one place. If everything works perfectly, the sufferer will not sustain major injuries.

3.2.4. Comparative Diagram of Rockwell Hardness Values for Several Materials, Including Commercially Available Polystyrene and Recycled Polystyrene

The waistcoat's components are meticulously picked. For example, the material that will be struck initially must have unique properties that allow it to function as a bumper.

The different Rockwell hardness values for the materials compared with polystyrene are presented in Table 9 below.

Table 9. Hardness value of different materials.

Material	Hardness value (%)
PS not recycled	0.7

Continued

PS recycled	65
Ceramic C/SiO_2	80
Steel	89

As a result, we will display the results of our testing using a graph (diagram), as illustrated in Figure 10.

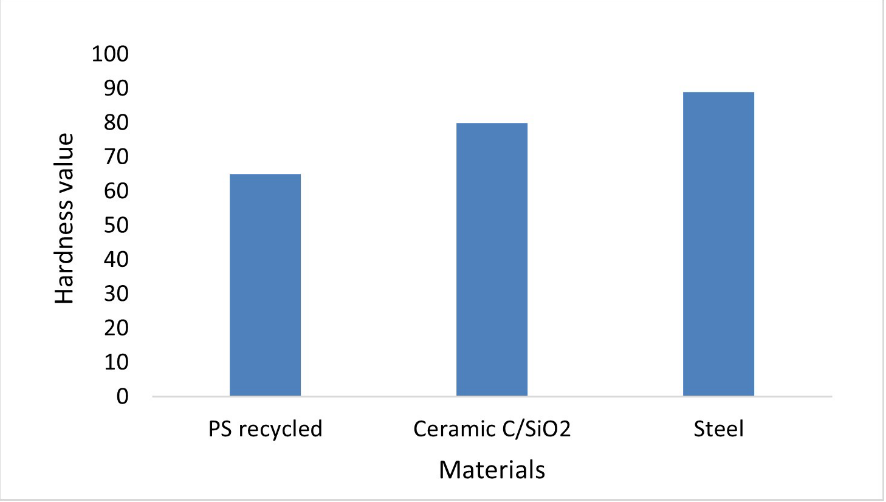

Figure 10. Rockwell hardness value of different materials.

We observe a significant difference in the hardness of polystyrene supplied on the market as bumper material for home appliances and that of the polystyrene we have recycled, with values lower than those of carbon/silica-based ceramics or, even more so, steel. This allows us to confirm our material's progressive mechanical qualities following recycling. Composite materials have been used in a variety of military applications, replacing metals, ceramics, and other ballistic materials. A material's ability to give protection (stopping a projectile in its tracks) on contact is determined by its hardness, which is critical when 'blunting' a projectile.

The mechanical tests produced for our application are the simple compressive strength and tensile tests, which were performed just on polystyrene specimens and not on the composite.

3.3. Tensile test

Table 10 below shows the results of the tensile tests carried out on the material.

Table 10. Elasticity limit values of different materials.

Material	Elasticity limit (MPa)
Kevlar	3000
PS not recycled	20
PS recycled	400

We will therefore represent the results of our tests in graphical form as shown in Figure 11 below.

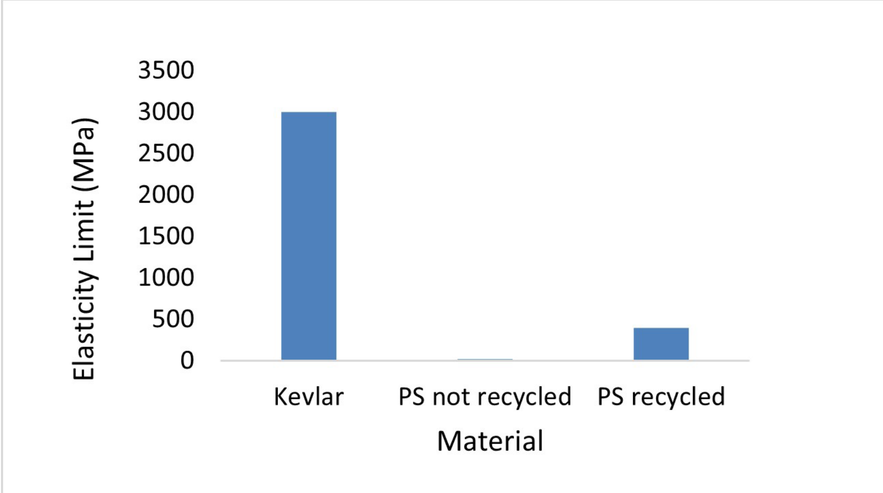

Figure 11. Elasticity Limit values of different material.

Figure 11 indicates that polystyrene recycled by solvolysis has 20 times greater tensile characteristics than expanded polystyrene. The rise in tensile and other properties can be attributed to the materials' structure prior to, during, and after dissolution and setting. Considering the contribution of the improved qualities of the recycled polystyrene to the composite material created a few tests on the composite materials were enough to make a preliminary conclusion on the efficiency of the technique used.

3.4. Elongation at break

Table 11 displays the fibre elongation at break values (in MPa) for some of the materials utilized in body armour design.

Table 11. Elongation at break values.

Material	Elongation break (MPa)
Glass E	3.5
Carbone Hm	0.6
Kevlar 49	7
Aluminium silicate	1.5
Bore	0.8
PS not recycled	4.5

The penetration of a drill with the above-mentioned parameters is measured in millimetres per second. This demonstrates the efficiency of the composite material produced in maintaining the projectile while it moves at high speeds, rotates, and pierces (helical movement). Body armour is intended to protect the torso from shards of exploding shells, grenades, shattered mines, and bullets fired from small guns. This armour protects against bullets of calibre.22 to.30, with a notional mass of 2.6 to 10 g and a velocity of 436 to 869 m/s when shot at 5 m (NIJ Standard 01.01.04).

Considering this, it becomes reasonable to conclude that the composite material has a high resistance and retention capacity, which is enhanced by the inversion of the woven silk threads. The maximum penetration of the bullet is 45˚ for 1 cm, therefore the composite has a value of 0.9 cm for 45˚ after 5 seconds.

Tests on genuine projectiles (ballistic kind) revealed that the waistcoat had a high retention capacity for handgun rounds, as indicated in Figure 12 below.

Figure 12. Prototype of the bulletproof vest.

4. Conclusions

The aim was to recycle plastics via solvolysis to create an impact-resistant composite material (like bulletproof waistcoats). The primary objective was to create a composite material with exceptional mechanical and ballistic capabilities while taking environmental concerns into account.

We chose a method of collecting raw material composed of polystyrene-based plastics. Non-probabilistic sampling, also known as the empirical or reasoned choice approach, involves a non-random selection of the material collected. This material was submitted to a variety of mechanical tests before being treated. For the treatment, we picked a process that would allow us to recycle in a less polluting way (solvolysis), therefore the material was immersed in a solution of copper sulphate [$CuSO_4$], potassium hydroxide [KOH], and limonene as the solvent. After recycling, the material is treated to a process that refines the material's qualities. After the process, we subjected the specimens to mechanical tests, yielding a composite material composed of a polystyrene matrix and reinforcing spider silk fibres with mechanical qualities such as hardness and durability.

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the metallography and rock mechanical laboratories.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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