

A Lightweight Advanced Composite System: Polypropylene Fabric Reinforced Expandable Polystyrene

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Abstract. Polymer matrix composite (PMCs) have the primary strengths of high specific strength, low density, and corrosion and abrasion resistance. Their performance is largely determined by the effectiveness of the transfer of loads between fiber reinforcement and polymer matrix. To produce a lightweight composite material, a polypropylene (PP) fabric was reinforced into an expandable polystyrene (EPS) matrix with gaseous softening and processing ingredient of gasoline. A composite was developed using the reinforcement in order to determine the effect of polypropylene reinforcement on the mechanical and physical behavior of an EPS-based matrix. The mechanical characterization tests such as tensile, flammability and hardness tests were performed in this research. It is found that besides increasing the surface hardness, the presence of polypropylene textiles also enhances the structural integrity, tensile responsiveness, as well as flame-resistance characteristics in the EPS matrix. The suggested work recognizes the potential of the PP-fabric-reinforced EPS composites as an example of a low-density material that can be used in the lightweight structural and insulating areas.

1 Introduction

1.1 Composites

Composites form a significant part of materials that are vastly utilized by and to our everyday requirements. Studies of the composites by metallurgists, material scientists, mechanical, civil and chemical engineers is transforming the research on materials, by utilizing it in an even more significant manner in engineering and other commercial fields. Composite: This

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involves the combination of two or more unlike materials to make new stronger materials. The component materials are individual particles which possess varied physical and chemical characteristics and possess diverse demarcations among their surfaces [1]. The significant constituents of the composites are fibre, matrix, and the interface. They are mostly carried out in two stages one being the reinforcement and the other being the matrix or resin. The hardness of the composites is based on the reinforcement stage. Forms of the reinforcements that are available include fibre, particles and flakes [2].

Overall, the matrix is a continuous phase and offers adhesive shear strength with low tensile and compressive characteristics. The composites involve the use of matrix materials as the glue [3]. The matrix or resin mostly surrounds individual reinforcement fibres. The role of the matrix is to transfer the load between fibres to the matrix and subsequently to the other fibres to the matrix. The tensile strength of the composites is also dependent on the fibre and the transfer of the load through shear strength by the matrix. The fiber reinforced composite has taken the limelight over the other forms of composites since most of the materials are stronger and stiffer in the fibrous form than in any other form [4].

Composite is a blend of two or more varied constituents which are contained in proportions required and possess various characteristics. The characteristics of a composite are not similar to those of non-composites or single material. As an example, plastic is not a composite, since it is a compound [5]. An alloy is not composite, in that it is a homogeneous mixture. The type of composite is determined by the character of the matrix and reinforcement used. Composites have wide applications in the military and the civilian industry. They are employed in the production of various products such as aircraft, 3 spacecrafts, satellites, missiles and rockets, sports goods, marine equipment, automobile parts etc and so on. The composites are made, and developed to achieve appropriate characteristics to be used.

1.2 Reinforcement

The second components are reinforcements that might combine with base matrix to enhance thermo-mechanical and tribological characteristics of the base matrix. Ordinarily the thermoset matrix can be extremely brittle hence its rigidity and toughness are extremely low. To enhance the strength and rigidity, secondary reinforcements such as fibre and particle may be incorporated together with the matrix so as to alter the properties of the base. In case of the properties modifications, then the composites may be employed to replace any metallic and non-sustainable material [6]. The plastics are yet to be at the mark in structural usage. In most cases, the part of natural fibre reinforcement could be the short or the long continuous fibre or occasionally the development of the particle size of micro or nano dimension. Even whiskers are being used today as reinforcement as whiskers does not contain any intense flaws in their crystal structure [7]. Reinforcement of a polymer matrix plays the role of enhancing the load bearing property of polymer, augmenting the thermal stability, ameliorating the abrasion, chemical and water resistance etc [8].

1.3 Particle Reinforced Polymers (PRPs)

The reinforcing of the composite material is done by adding particles like ceramics, glasses and amorphous materials etc, in order to increase the modulus, also to soften the ductility of the matrix. Particles are thus added to reduce the cost of the composites. Reinforcement and matrices of composites are inexpensive as well as easy to process. Some of the outstanding properties of ceramic and glass particles include high melting point, low density, high strength, rigidity; wearability, and corrosion resistance [9]. The magnetic and

piezoelectric material properties can be found in some of the ceramics even though they are considered as good electrical and thermal insulator. Even a super conductor is also a rare occurrence in ceramics at relatively low temperatures. The typical disadvantage of particle of ceramic and glass is that, it is brittle. One such example of automobile tyres is particle reinforced polymer. It has black particles of carbon in polyisobutylene elastomeric polymer. There have been many interests in aerospace regarding polymer composite materials as well. Specific composites organization [10]. Research is being carried out intensively all over the globe in an effort to discover newer composites with varying fibre contents. The ultimate objective of the research that will be implemented is to make them applicable to different working conditions [11].

1.4 Fibre Reinforced Polymers (FRPs)

Fiber reinforced composites is the combination of fibers and matrix. Fibers that give strength to the composites are the reinforcements. The matrix contains the fibers and it also distributes the stresses among the reinforced fibers. The loads applied to the fibers in longitudinal directions. In other instances, fillers are incorporated to facilitate the manufacturing process and also to give the composites some special characteristics. This minimizes the product cost as well [12]. Typical fiber reinforcing agent The frequently used fiber reinforcing agents are asbestos, beryllium oxide, glass fibers, natural fibers, etc. Typical matrix material The most common are epoxy, polyetheretherketone (PEEK), vinyl ester, etc. The adhesion and shrinkage characteristics of epoxy is greater compared to PEEK that occupies second position in use. This is because of its expensive cost.

The paper, Salini, N G, defines the Dispersion of starch and ENO in EPS/EVA matrix providing biodegradability denoting its usability in packaging. EPS/EVA thin films with calcium oxide, zinc oxide, kaolin and bentonite as the components showed better barrier against hydrocarbon fuel e.g. kerosene, petrol and diesel. They are more thermal stable and mechanically stronger. When EPS was pyrolyzed in the presence of bentonite, mesoporous carbonaceous char was obtained with very high photo catalytic activity in the degradation of organic dyes. Silver doped TiO₂ nano particles as composite thin films showed better adsorbent ability in the removal of COD in the aqueous effluents. EPS/PVA blend film was found to have great vapor permeability of aliphatic alcohols such as methanol, ethanol and 2-propanol. The enhanced ability to absorb water and high level of swelling was an indication of its hydrophilic nature [13].

P. Sathyaseelan, Hybrid laminates are laminates produced with natural fibers which have been finding in use in various applications e.g. automobiles parts, structure of a building and sports items. These laminates will have the advantages of the reinforcements employed in its constructions. This paper is concerned with the manufacture of hybrid laminate of a natural fiber areca and kenaf in different stacking arrangements using a hand layup process. The ratio of the epoxy resin (LY556) and hardener (HY951) is 10:1, used to prepare the matrix material. There are five layers of areca and kenaf hybrid laminates produced in six variations in varied stacking arrangements. Two additional laminates with either kenaf or areca in all of the five layers are made to serve as the reference laminate. The ready laminates are cut according to ASTM specifications and then they are tested on tensile, compressive, flexural, impact and hardness tests. In the same way, thermal characteristics such as thermal conductivity, heat deflection temperature, coefficient of linear thermal expansion are analyzed [14]. The last stage is the dynamic mechanical analysis of the hybrid composites which is used to determine the characteristics of fabricated laminates. The finding indicates that composite comprising of kenaf fiber as skin material and areca as core material has better tensile, flexural and hardness properties. Similarly, those that are made of areca and kenaf fibers on the outside and core layers respectively have high compressive and impact strength.

Content of kenaf fibre in the composite determines the loss modulus of the hybrid composite. The less kenaf fiber composites had optimum loss modulus. Kenaf fiber content in composite laminates had lower water absorption in the water absorption test [13][14].

The mechanical characteristics of areca fiber composite produced using polypropylene polymer for automotive components were examined by Pavankalyan, Paul, and Kamalakannan (2018). composites with 5, 10, and 15 weight percent areca fibers. The results demonstrated that, in comparison to the other composites employed in the study, the composites with 5 weight percent exhibited superior mechanical qualities [15]. Because of the poor bonding between the reinforcement and the matrix, further increases in areca fiber concentration reduce strength.

G Aravinthan, Research on Polypropylene and Cyclic Olefin Copolymer Blend Nanocomposites Reinforced with Halloysite Nanotubes. Polymer blends and nanocomposites are widely employed to create new materials that are more cost-effective and have better qualities than individual polymers[16]. One of the adaptable plastic compounds frequently utilized in the production of industrial and domestic goods is polypropylene (PP). A common amorphous engineering plastic used in the production of medical syringes, food packaging containers, and optical devices is cyclic olefin copolymer (COC). Because both polymers contain olefinic components, PP/COC blends were made in this study using a co-rotating intermeshing twin screw extruder over the whole composition range with a 10-weight percentage COC content increment without compatibilizer [17]. In terms of various physicochemical characteristics and superior processability when compared to pure PP and COC, respectively, a 50/50 PP/COC blend was found to be the ideal blend composition. To create nanocomposites, a 50/50 PP/COC matrix was mixed with 1, 2, 3, and 5 weight percent of halloysite nanotubes (HNT), respectively. Overall excellent characteristics were demonstrated by PP/COC based nanocomposites with three weight percent HNT nanofiller. The produced blends and nanocomposites' mechanical, thermal, rheological, structural, and morphological behaviours were carefully examined [18].

Prabh.T. Niranjana, Four polymer composites were created for these studies: Epoxy-Nylon fabric-Clay Composite Laminates, Epoxy-Unsaturated Polyester-Clay Composites, Epoxy-HDPE fabric-Clay Composite Laminates, and Epoxy-Polypropylene short fibers-Clay Ternary Composite hybrids [19][20]. Through a review of the literature, these materials were carefully chosen to make appropriate structural materials and were investigated for their mechanical, thermal, and flame-retardant qualities [21][22]. The study's primary goal was to determine how well these materials adapt to mechanical, thermal, and fire stressors. Using the open mould casting approach, the aforementioned unsaturated polyester composites, epoxy-fabric-clay composite laminates, and epoxy-short fiber-clay ternary composite hybrids were created with varying compositions [23]. At reduced clay loading, clay particles exhibit good dispersability in the resin, according to SEM analyses of the composites for filler dispersion. However, tactoid forms have been seen at higher clay loading levels [24][25].

2 Materials and Methods

2.1 Materials

The raw material of this study is expanded polystyrene is used. Molecularly polypropylene is a stereoregular catalytically derived polymer of propylene. It has a carbon-carbon backbone with pendant methyl groups whose spatial geometry outlines three main tacticities, namely, isotactic, syndiotactic, and atactic. With the methyl groups in the same side of the chain, isotactic PP has high crystallinity and is the most commonly used commercial grade, with a melting temperature of 160-166 °C. Syndiotactic PP, where methyl groups are

alternated, assume a specific crystalline structure, whereas atactic PP, with randomly substituent, is mainly amorphous, and has poor mechanical properties. The morphology of PP has many phases that include crystalline (α , β and γ polymorphs), mesophase (paracrystalline/smectic) and amorphous regions and the phase composition is highly dependent on the stereoregularity, molecular weight distribution and processing conditions. The Table 1 shows the properties of Polypropylene used in this study [26]. This composite has a gasoline-softened EPS matrix which is thermoplastic and does not physically crosslink during its curing. Hardening is due to removal of solvents and entanglement of chains, and not the creation of an interlaced polymer network.

Table 1. Properties of Polypropylene.

Properties	Values
Elastic modulus (MPa)	735 – 1470
Shear modulus (MPa)	265 – 529
Poisson's ratio	0.4
Thermal expansion coefficient (1/K)	$1.134 - 1.49 \times 10^{-4}$

2.2 Preparation of Composite

The composite system's matrix material was created by dissolving Expanded Polystyrene (EPS) in gasoline as a solvent. The matrix was manually made in a container impervious to polymers. A blend of 70 wt.% EPS and 30 wt.% gasoline was mixed for 10 to 15 minutes to enhance solvent-polymer interaction. During this interval, gasoline caused fast depolymerization and volumetric collapse of the EPS, leading to the dissolution of the polymer beads and the release of the entrapped air cells characteristic of the enlarged structure. This reaction produced a semi-solid, foam-like resin. Given the significant volatility of gasoline and its quick evaporation during breakdown, continual agitation was essential to reduce air entrapment and maintain uniform resin consistency. Insufficient mixing results in the entrapment of air bubbles inside the viscous matrix, negatively impacting mechanical integrity; hence, continuous stirring was sustained until a uniform resin phase was achieved [27].

The composite was fabricated with an open-mold hand lay-up technique. Polypropylene (PP) sheets, dimensioned at 200 x 200 mm, functioned as the reinforcing substrate. The PP layers were positioned on a glass surface to facilitate effortless demolding. The formulated EPS-gasoline resin was uniformly applied to one surface of the PP with a brush to guarantee sufficient wetting and interfacial adhesion. The laminate underwent initial curing for 24 hours, followed by complete curing within 48 hours. Upon complete curing of the initial surface, the reverse side of the PP sheet was covered and underwent the identical curing procedure. Composite specimens were constructed at three different thickness levels to assess structural and performance changes related to matrix deposition.

Test specimens were fabricated in compliance with the dimensional criteria outlined by applicable ASTM standards. The composite coupons were manufactured to a nominal dimension of 12.7 cm in length and 1.27 cm in breadth for this study. The dimensions were constantly maintained across all samples to guarantee uniformity during later mechanical characterization.

Significant issues with air entrapment in the EPS–gasoline matrix arose during the initial fabrication attempts. Inadequate mixing resulted in the retention of microbubbles within the semi-solid resin, and the breakdown of EPS naturally releases significant amounts of trapped air. These defects caused early fracture during testing by impairing matrix continuity, reducing composite stiffness, and significantly lowering load-carrying capacity. Similar issues were observed during the coating phase, when interfacial inadequacies were made worse by insufficient wetting of the polypropylene (PP) reinforcement.

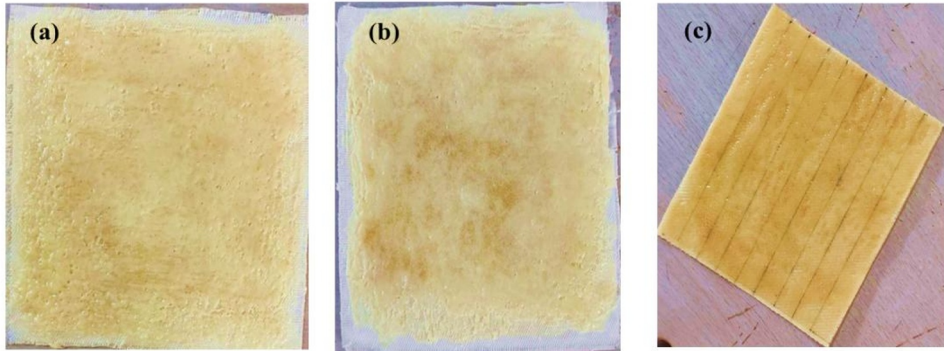


Fig. 1. Prepared sample material (a) 3 mm thickness, (b) 2 mm thickness, (c) 1 mm thickness.

To address these issues and improve the preparation procedure, we conducted numerous trials repeatedly. The matrix was blended more and more to reduce the production of bubbles, and the application of controlled resin improved its adhesion to the PP substrate. By carefully adjusting the production parameters, flawless composite sheets were produced. Three group of various thickness of 1 mm, 2 mm, and 3 mm were used to create the finished samples. This allowed the effectiveness of the samples to be compared according to their thickness. Every prepared sample had sufficient structural integrity for testing and complied with the size restrictions. Fig.1 shows the composite material prepared for testing. The gasoline softened EPS matrix follows chemical bonding, and mechanical interlocking between the polypropylene reinforcement and van der Waals attraction is involved secondary support of the polypropylene reinforcement secondary and diffusion bonding or chemical bonding is nonexistent.

3 Materials Testing

3.1 Sample Preparation, Standards and Testing

The physical and mechanical characterization of polymeric materials is a very important aspect of quality control and product development. A comprehensive study of aging behavior under mechanical, thermal, optical, rheological, and environmental conditions to provide important information regarding the relationship between structural property and formulation, processing and end-use performance are to be optimized. Mechanical and physical testing is applied especially in such sectors as aerospace, automotive, medical devices, consumer goods, and military to ensure that polymers meet the very stringent demands of industry-specific rules and global standards.

Rigorous characterisation is needed to measure operating limits, failure modes and long-term durability of materials because the chemistries, morphologies, reinforcing systems, and additive packages of plastics are very diverse. To polymer suppliers, compounders and

product designers, this type of data is useful in making informed decisions across the entire polymer supply chain, ensuring reliability, safety, and regulatory safety in the contemporary polymer uses.



Fig. 2. Sample for material characterization.

Keeping these considerations in mind the test parameters have been decided and the samples were prepared based on ASTM standards for various testing procedures as shown in Fig.2, which is discussed below.

ASTMD 638 states that tensile test is carried out on a Universal Testing Machine (UTM) under dimensions of 115x 19x 5 mm with a strain rate of 5 mm/min. The flexure test specimen was prepared in compliance with the ASTM D 790 where the specimen dimensions were set at 80 x 13 x 5 mm. The three-point bending test was done at room temperature using the same UTM. A 600 KN load cell and 5 mm/min crosshead speed were added to the setup to give it strength. Test of impact was done using a machine of impact testing. Unnotched specimens were used to make sure that the data obtained through experimentation give an actual image of the composite with real-world impacting conditions. All the fibers/matrix ratios will be tested on specimens testing 64 x13x5 mm³ as per ASTM D 256 standards.

Hardness test was conducted on the prepared sample as per ASTM D2240 standards at six different locations. A universal testing machine (UTM) was used to perform peel tests in order to assess the composite laminates' interfacial adhesion. Under the same loading circumstances, specimens with matrix thicknesses of 1 mm, 2 mm, and 3 mm were made and examined.

4 Results & Discussion

4.1 Tensile Test

Four types of specimen of composite laminates with different thickness and neat fabric were subjected to tensile characterisation. The Table 2 gives an overview of the relevant tensile results. The fact that the fabric was not reinforced with a matrix was reflected in the lowest tensile bearing capacity of the tidy fabric. Composite specimens, all of which demonstrated significantly higher tensile strength, however, demonstrated a steady increase in maximum tensile force with matrix thickness. This trend indicates that the higher the concentration of resin, the higher the level of fiber-matrix bond, and the transfer of load.

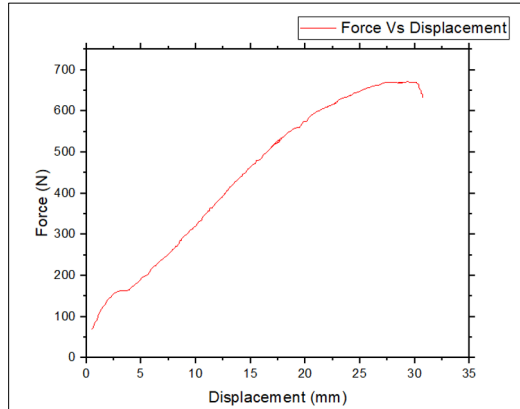


Fig. 3. Force – Displacement Curve.

Table 2. Tensile Strength of Composite Material.

Test Samples	Load (N)	Displacement (mm)	Tensile Strength (MPa)
Neat Fabric	620	30	24.4
1 mm thickness composite material	750	31	58.8
2 mm thickness composite material	850	29	33.46
3 mm thickness composite material	1000	30	26.8

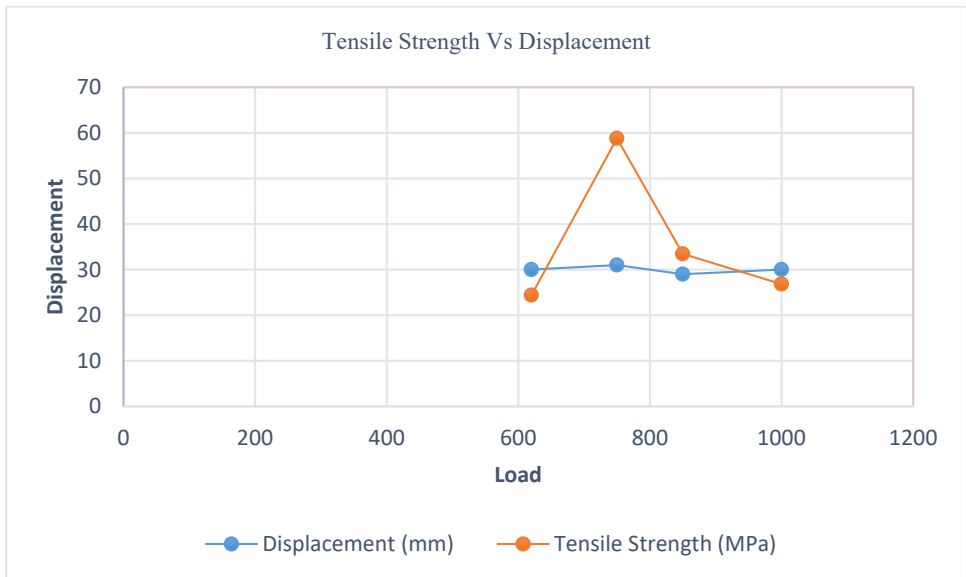


Fig. 4. Comparison of Tensile Strength Vs Displacement w.r.t the applied load.

As given in the Fig.3.the force rises to about 0 N up to about 150-200 N during the first few mm of the force-displacement curve pointing to a non-linear area at the beginning. This early increase normally relates to the commencement of crack propagation and removal of localized interfacial imperfection. Later in the curve, it can be seen that the growth of fractures on the bonded interface is constant, since the curve takes a more linear and continuously rising shape. At approximately 27-28 mm, the stroke, the peel force is at its peak and is approximately 650-680 N. Then, it slowly creeps up with stroke. At this stage, when the residual bonded area of the two bodies reduces and when the force required at the stage starts to reduce, then the plateau or slight decrease at the end is an indication of the commencement of the interfacial failure completion.

4.2 Peel Test

Peel testing was used to measure the interfacial adhesion strength of composite laminates with 3 different thickness of the matrix using a universal testing machine (UTM). Table 3 summarises the respective peel forces that were obtained in each setup. Though further increase in the thickness of the matrix is likely to enhance the interfacial bonding and consequently enhance the resistance to peel, the experimental findings show that there is a slight variation only. This is an indication that an interfacial fiber-matrix adhesion is mostly determined by interfacial properties between the fibers and the matrix, but not by bulk matrix volume because the content of the matrix does not have a significant influence on peel strength over the measured thickness range.

Table 3. Peel Test Force- Stroke.

Test Samples	Force (N)	Stroke (mm)
1 mm thickness composite material	50	325
2 mm thickness composite material	55	319
3 mm thickness composite material	60	305

4.3 Hardness Test

Hardness was tested using a Shore A durometer to a test procedure as per the ASTM standard protocol. To ensure the averaging of the representatives, 6 points were used on each sample of the composite specimens with the matrix thicknesses of 1 mm, 2 mm, and 3 mm to measure the hardness values. The average hardness of the 1 mm specimen was 84 and Table 4 indicated an average hardness of 85 in the 2 mm specimen. The mean of the 3 mm specimen was 84. The narrow band of values that have been measured was an indication that there was not much impact on the Shore A hardness of the composite material by the thickness of the matrix in the range of measurements.

Table 4. Hardness Test Results.

Test Samples	Hardness
1 mm thickness composite material	83
2 mm thickness composite material	85
3 mm thickness composite material	85

4.4 Structural Characterization of Composite using X-Ray Diffraction

The crystalline and amorphous properties of the composite material were investigated using X-ray diffraction (XRD) research. Fig. 5, displays the obtained diffraction pattern. To determine whether crystalline phases were present and to assess the material's structural ordering, the sample was scanned throughout a 2θ range of 0° to 80° .

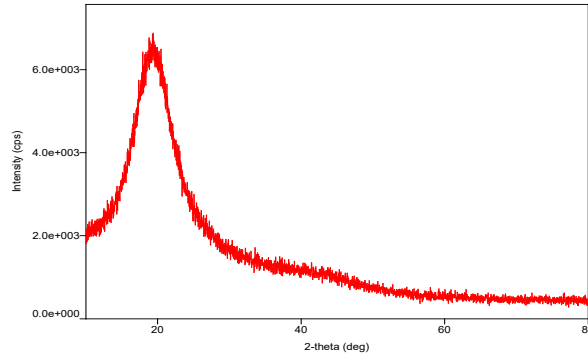


Fig. 5. XRD Analysis of the composite Material.

There are no distinct peaks seen across the scanning range, and the XRD pattern displays a broad diffraction hump centred about $2\theta = 18\text{--}22^\circ$. The absence of long-range periodic arrangement in the molecular chains of amorphous and semi-crystalline polymeric materials is characterised by this broad, diffuse peak. The material's limited crystallographic domains are confirmed by its huge full width at half maximum (FWHM) and lack of noticeable Bragg reflections.

4.5 Flammability Test



Fig. 6. Flammability Test Apparatus.

According to the standard test protocol, horizontal flammability testing was carried out to assess the composite laminates' burning behaviour and flame-propagation properties. The time it took for the flame front to move across the designated marking distance on each sample was used to calculate the flame-spread rate for specimens with matrix thicknesses of 1 mm, 2 mm, and 3 mm. For the 1 mm specimen, the measured burn rate was 52 mm/min; for the 2 mm specimen, it was 56 mm/min; and for the 3 mm specimen, it was 58 mm/min.

5 Conclusion

This research investigated the polypropylene fabric reinforced extended polystyrene composites of different fiber content for tensile, Hardness, Peel test, and flammability.

- The tensile strength increased from 24.4 MPa to 33.46 MPa in the 2 mm thickness composite material which shows 9 % increase in the tensile strength.
- According to the hardness measurement, the fiber-reinforced composite maintains a constant surface hardness at the specified fibre loading, with a Shore A value of roughly 84.
- The results of the peel test suggest that matrix thickness does not have a significant effect on interfacial adhesion, which proves that the peel strength is mainly determined by the fiber-matrix interfacial properties rather than the volume of the matrix.
- From the XRD Analysis, the wide diffraction peak that is concentrated around 20deg is a confirmation that the composite material has mostly an amorphous form with an insignificant contribution of crystalline phases.

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