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Experimental Study on the Mechanical and Morphological Properties of S_2-Glass/Phenolic Composite for Fire-Resistant Panels

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Abstract—

Fire-resistant polymer matrix composites have gained considerable importance in structural, transportation, and infrastructure applications due to increasing fire safety requirements combined with the demand for high mechanical performance. In the present study, compression-moulded S2 glass fiber reinforced phenolic composites incorporating 15 wt.% ammonium polyphosphate (APP) were developed and experimentally investigated for fire-resistant panel applications. The composite laminates were fabricated using bidirectional woven S2 glass fabric and resol-type phenolic resin through compression moulding to achieve uniform consolidation, controlled thickness, and reduced void content. Mechanical characterization was carried out using tensile, flexural, and Izod impact testing according to ASTM standards. The developed composite exhibited tensile strengths in the range of 260–300 MPa with tensile modulus values close to 10 GPa, indicating effective stress transfer between fibers and matrix. Flexural testing revealed strengths between 410–430 MPa with flexural modulus around 15 GPa, demonstrating excellent bending performance without severe degradation due to APP incorporation. Impact testing confirmed moderate energy absorption capability despite the brittle nature of phenolic matrices. Fire retardancy was evaluated using UL-94 testing, where the composite exhibited self-extinguishing behavior, reduced flame propagation, and no dripping characteristics due to APP-induced char formation. Morphological analysis using scanning electron microscopy (SEM) revealed strong fiber–matrix adhesion with limited interfacial debonding, while Energy Dispersive X-ray Spectroscopy (EDS) confirmed the uniform distribution of phosphorus-rich APP within the matrix and char layer. The experimental findings demonstrate that the developed S2 glass/phenolic/APP composite provides an effective balance between mechanical integrity and fire resistance, making it suitable for advanced fire-resistant structural panel applications.

***Key Words*: S2 glass fiber, Phenolic composite, Ammonium polyphosphate, Compression moulding, Mechanical properties, Fire resistance, SEM–EDS morphology.**

I. INTRODUCTION

The increasing demand for materials capable of simultaneously withstanding mechanical loading and resisting fire-induced degradation has accelerated research into advanced polymer matrix composites. In modern engineering sectors such as transportation, aerospace interiors, building panels, electrical enclosures, and defense infrastructure, fire safety has become a critical design requirement alongside strength-to-weight efficiency. Conventional metallic materials, although non-combustible, suffer from disadvantages such as high density, corrosion susceptibility, and limited design flexibility. In contrast, fiber reinforced polymer (FRP) composites provide superior specific mechanical properties, corrosion resistance, and ease of fabrication; however, their inherent flammability and smoke generation restrict their application in fire-critical environments. Consequently, the development of fire-resistant composite systems capable of satisfying both structural and safety requirements has become an important area of research.

Among thermosetting matrices, phenolic resins are widely recognized for their excellent flame-retardant characteristics, including low heat release rate, reduced smoke emission, and high char yield during thermal degradation. Unlike epoxy or polyester resins, phenolic materials undergo char-forming decomposition, thereby reducing the release of combustible volatile compounds and providing passive fire protection. Due to these advantages, phenolic-based composites are extensively utilized in aircraft interiors, railway applications, fire-resistant panels, and thermal insulation systems. However, phenolic matrices are inherently brittle and possess relatively low fracture toughness and impact resistance, which limits their use in structural load-bearing applications without suitable reinforcement.

The reinforcement phase significantly influences the mechanical performance of phenolic composites. Glass fibers are among the most commonly used reinforcements because of their cost-effectiveness, chemical stability, and compatibility with thermosetting matrices. Among different glass fiber grades, S2 glass fibers represent a high-performance reinforcement possessing superior tensile strength, elastic modulus, and thermal stability compared to conventional E-glass fibers. These characteristics make S2 glass fibers highly suitable for applications requiring enhanced mechanical reliability under both ambient and elevated temperature conditions. Nevertheless, the interaction between S2 glass fibers and phenolic matrices, particularly in the presence of flame-retardant additives, requires systematic investigation to establish structure–property relationships relevant to fire-resistant structural panels.

To further improve flame resistance, polymer composites often incorporate flame-retardant additives capable of suppressing ignition, flame propagation, and heat release. Among various flame-retardant systems, intumescent additives have attracted considerable attention because of their effectiveness and comparatively lower environmental impact. Ammonium polyphosphate (APP) is one of the most widely used intumescent flame retardants and primarily functions in the condensed phase. During thermal exposure, APP decomposes to form phosphoric acid derivatives that promote dehydration and carbonization of the polymer matrix, resulting in the formation of a thermally stable expanded char layer. This protective char acts as a physical barrier that limits heat transfer and oxygen diffusion, thereby enhancing fire resistance. The combination of APP with phenolic resin systems is particularly advantageous because phenolic matrices inherently possess strong char-forming capability, leading to synergistic flame-retardant behavior.

Although APP significantly improves fire performance, its incorporation within fiber reinforced composites can affect resin viscosity, curing behavior, and fiber–matrix interfacial bonding. Improper dispersion or excessive loading of flame-retardant additives may introduce stress concentration sites that lead to premature mechanical failure. Therefore, achieving an optimum balance between mechanical integrity and fire resistance remains a major challenge in the development of flame-retardant composites. This emphasizes the necessity for detailed experimental investigations that evaluate both fire behavior and mechanical performance simultaneously.

The fabrication method adopted for composite manufacturing also plays a crucial role in determining laminate quality, fiber wetting, void content, and interfacial adhesion. Compression moulding is a widely used fabrication technique for thermosetting composites and is particularly suitable for producing flat laminates with controlled thickness and uniform consolidation. Compared with hand lay-up methods, compression moulding offers improved dimensional accuracy, lower porosity, enhanced repeatability, and superior laminate quality. Furthermore, the application of pressure during curing improves resin flow and fiber impregnation, which is especially important for relatively high-viscosity phenolic resin systems.

Mechanical characterization is essential for evaluating the structural performance of composite materials. Tensile testing provides insight into stress transfer efficiency between fibers and matrix under uniaxial loading conditions, while flexural testing evaluates composite behavior under combined tensile and compressive stresses representative of practical panel applications. Impact testing is particularly important for phenolic composites because it determines the ability of the material to absorb sudden loading despite the brittle nature of the matrix. Collectively, these mechanical tests provide a comprehensive understanding of the suitability of the developed composite system for fire-resistant structural applications.

In addition to mechanical evaluation, morphological characterization provides valuable insight into the microstructural features governing composite performance. Scanning Electron Microscopy (SEM) enables detailed examination of fracture surfaces, matrix cracking, fiber pull-out, and interfacial debonding, thereby revealing failure mechanisms associated with different loading conditions. When combined with Energy Dispersive X-ray Spectroscopy (EDS) and elemental mapping, SEM analysis also facilitates the investigation of flame-retardant element distribution and char morphology after fire exposure. Such analyses are essential for correlating mechanical behavior with flame-retardant mechanisms and validating the effectiveness of APP within the phenolic matrix system.

Despite the growing research interest in fire-resistant polymer composites, limited studies have systematically investigated compression-moulded S2 glass reinforced phenolic composites containing ammonium polyphosphate. Most existing studies focus either on fire behavior or mechanical performance independently, with comparatively less emphasis on the interrelationship between microstructure, mechanical integrity, and flame-retardant performance. This research gap highlights the need for integrated experimental studies capable of simultaneously evaluating mechanical, morphological, and fire-resistant characteristics within a single composite system.

Therefore, the present study aims to develop and experimentally evaluate compression-moulded S2 glass fiber reinforced phenolic composites incorporating ammonium polyphosphate as a flame-retardant additive for fire-resistant panel applications. A comprehensive investigation involving tensile, flexural, and impact testing together with SEM and EDS characterization was carried out to establish clear structure–property relationships governing the developed composite system. The findings of this work are expected to contribute toward the advancement of fire-resistant phenolic composites for safety-critical engineering applications.

II. LITERATURE REVIEW

The literature related to S2 glass reinforced phenolic composites containing intumescent flame-retardant additives mainly focuses on the properties of S2 glass fibers, thermal and fire-resistant behavior of phenolic resins, the flame-retardant mechanism of ammonium polyphosphate (APP), processing techniques such as compression moulding, and the influence of additives on mechanical and morphological characteristics. These studies provide important insights into the design and development of fire-resistant structural composite systems.

S2 glass fibers possess significantly higher tensile strength, elastic modulus, and thermal stability compared to conventional E-glass fibers. Previous investigations reported approximately 15–25% improvement in tensile and flexural properties for S2 glass reinforced composites when compared with E-glass based systems [1–3]. Due to their superior mechanical reliability under elevated temperature conditions, S2 glass fibers are extensively utilized in aerospace structures, pressure vessels, and high-performance composite panels [3,4]. The effectiveness of S2 glass reinforcement strongly depends on fiber orientation, interface quality, and compatibility with the matrix system.

Phenolic resins are widely recognized for their excellent flame-retardant properties because of their inherent char-forming decomposition mechanism. Unlike epoxy and polyester systems, phenolic matrices exhibit low heat release rate, low smoke emission, and high residual char formation during thermal degradation [4,12]. Thermogravimetric studies reported that the thermal stability and decomposition characteristics of phenolic resins are strongly influenced by curing conditions and crosslink density [12]. However, phenolic resins are inherently brittle and exhibit comparatively lower fracture toughness, thereby requiring reinforcement with high-strength fibers for structural applications.

Ammonium polyphosphate (APP) is one of the most commonly used intumescent flame retardants in thermosetting polymer systems. APP primarily functions in the condensed phase by generating phosphoric acid derivatives during thermal decomposition, which promote dehydration and carbonization of the polymer matrix [17,21]. The resulting expanded char layer acts as a thermal barrier, limiting heat transfer and suppressing flame propagation. Several studies reported that APP incorporation significantly improves UL-94 flame-retardant performance and increases limiting oxygen index (LOI) values in phenolic composites [9,21]. Nevertheless, excessive APP loading can negatively affect resin flow behavior, increase brittleness, and introduce stress concentration sites that reduce mechanical performance [13,21]. Therefore, maintaining proper APP dispersion and optimum additive concentration is essential for balancing flame retardancy and structural integrity.

The fabrication process also plays a critical role in determining laminate quality and mechanical behavior. Compression moulding is widely recommended for phenolic composites because it provides superior laminate consolidation, lower void content, improved dimensional accuracy, and enhanced repeatability compared to hand lay-up techniques [2,10]. The application of pressure during curing improves resin flow and fiber impregnation, which is especially beneficial for high-viscosity phenolic systems. Previous investigations emphasized that curing temperature, pressure profile, and dwell time significantly influence void formation, interfacial adhesion, and overall composite performance [18].

Mechanical investigations on APP-modified glass fiber reinforced phenolic composites revealed that moderate APP concentrations between 5–15 wt.% can provide considerable improvement in fire resistance while maintaining acceptable tensile and flexural properties [9,14,21]. Some researchers observed that phosphorus-containing species generated from APP decomposition may improve local crosslinking and interfacial adhesion, whereas others reported increased brittleness due to particulate stress concentration [6,21]. Consequently, maintaining strong fiber–matrix adhesion remains a key requirement for achieving high mechanical performance in flame-retardant composites.

Morphological investigations using Scanning Electron Microscopy (SEM) consistently identified fiber fracture, cohesive matrix cracking, and limited fiber pull-out as dominant failure mechanisms in well-bonded phenolic composites [11,18]. SEM analysis of post-fire residues in APP-modified systems revealed the formation of continuous phosphorus-rich intumescent char structures. Energy Dispersive X-ray Spectroscopy (EDS) and elemental mapping confirmed phosphorus enrichment within the char layer, validating the effectiveness of APP in improving thermal stability and flame resistance [16,17]. These microstructural observations are important for understanding the relationship between mechanical behavior and fire-retardant performance.

Although considerable research has been carried out on phenolic matrices, S2 glass reinforcements, and APP flame retardants individually, comparatively limited studies have systematically investigated compression-moulded S2 glass/phenolic composites containing APP while simultaneously evaluating mechanical, fire-resistant, and morphological properties [2,9,16]. In addition, the relationship between processing conditions, APP dispersion, void formation, and mechanical performance is not comprehensively reported in the existing literature. Therefore, the present work focuses on developing and experimentally evaluating compression-moulded S2 glass reinforced phenolic composites containing APP for fire-resistant panel applications through integrated mechanical, fire, SEM, and EDS analyses.

III. MATERIALS AND MANUFACTURING

The composite system investigated in the present study consists of high-performance S2 glass fiber reinforcement, a phenolic resin matrix, and ammonium polyphosphate (APP) as an intumescent flame-retardant additive. All materials were procured from established Indian suppliers to ensure availability, traceability, and reproducibility. The selection of materials was guided by their mechanical performance, thermal stability, compatibility with compression moulding, and relevance to fire-resistant panel applications.

3.1 S2 Glass Fiber Reinforcement

High-strength S2 glass fiber was employed as the primary reinforcement material due to its superior tensile strength, elastic modulus, and thermal stability compared to conventional E-glass fibers. Bidirectional woven S2 glass fabric with a nominal areal density of 220 g/m² was used in this study to achieve balanced in-plane mechanical properties and uniform load distribution under tensile and flexural loading conditions. The woven architecture also facilitates effective resin impregnation and laminate consolidation during compression moulding.

In India, S2 glass fiber fabrics are supplied through authorized distributors sourcing from AGY Holding Corp.. The fibers are surface-treated with a proprietary silane-based sizing compatible with phenolic resin systems, eliminating the need for additional surface treatments prior to fabrication. The high softening temperature and chemical inertness of S2 glass fibers make them particularly suitable for fire-resistant composite applications where structural integrity must be retained under thermal exposure.

3.2 Phenolic Resin Matrix

A thermosetting phenolic resin was selected as the matrix material owing to its inherent flame retardancy, low smoke generation, and high char yield during thermal decomposition. The phenolic resin used in this work was a resol-type resin, which undergoes self-curing through condensation reactions without the need for external curing agents. Resol phenolic resins are preferred for compression moulding processes due to their relatively lower curing temperature and good flow characteristics under pressure.

The resin was procured from an Indian phenolic resin manufacturer such as SI Group India or Atul Ltd., both of which supply industrial-grade phenolic resins for high-temperature and fire-resistant applications. The selected resin exhibits good adhesion to glass fibers, adequate thermal stability, and compatibility with particulate flame-retardant additives. During curing, the phenolic matrix forms a highly crosslinked network, which contributes to char formation and dimensional stability under fire exposure, albeit with inherently brittle mechanical behavior that necessitates fiber reinforcement.

3.3 Ammonium Polyphosphate (APP) Flame Retardant

Ammonium polyphosphate (APP) was incorporated into the phenolic matrix as an intumescent flame-retardant additive at a concentration of 15 wt.%. APP is a phosphorus-based inorganic compound widely used in fire-retardant polymer systems due to its effectiveness in promoting condensed-phase char formation. Upon exposure to elevated temperatures, APP decomposes to release phosphoric acid derivatives, which catalyze dehydration and carbonization reactions within the polymer matrix, leading to the formation of a protective, thermally stable char layer.

The APP used in this study was procured from Indian chemical suppliers such as Prasol Chemicals Ltd. or Loba Chemie Pvt. Ltd., which provide industrial and laboratory-grade flame-retardant chemicals. The selected APP grade possesses good thermal stability under processing conditions and exhibits minimal hygroscopicity, which is essential for maintaining consistent resin viscosity and curing behavior. Proper dispersion of APP within the phenolic resin was ensured to avoid agglomeration, which could otherwise act as stress concentrators and adversely affect mechanical performance.

3.4 Composite Configuration and Material Proportions

The composite laminates were designed with a glass fiber to resin ratio of approximately 65 (including APP):35 by weight, incorporating 15 wt.% of APP as part of the resin system. The S2 glass fabric layers were stacked in a [0/90] orientation to obtain quasi-balanced mechanical properties suitable for panel-type structures. Compression moulding was employed to consolidate the laminate, enabling effective resin flow, uniform fiber wetting, and reduced void content despite the presence of particulate APP.

Table 1. Properties of materials

Material	**Supplier (India)**	**Form**	**Key Technical Properties**
S2 Glass Fiber	AGY (via Indian distributors)	Bidirectional woven fabric (220 GSM)	Tensile strength: ~4.6–4.9 GPa; Elastic modulus: ~86–90 GPa; Density: ~2.46 g/cm³; High thermal stability (>800°C softening)
Phenolic Resin (Resol type)	SI Group India / Atul Ltd.	Liquid thermoset	Density: ~1.2 g/cm³; Glass transition temperature: ~150–180°C; High char yield; Low smoke emission
Ammonium Polyphosphate (APP)	Prasol Chemicals / Loba Chemie	Solid powder	Decomposition onset: ~300°C; Phosphorus content: ~31%; Non-halogenated; Intumescent behavior
Composite Laminate	In-house fabrication	Compression-moulded laminate	Fiber & filler content: ~65 wt. %; Balanced [0/90] layup; Thickness ~3 mm

Bidirectional S2-Glass Fabric

Phenolic Resin Matrix, Reactor and Catalyst

Ammonium Polyphospate (APP)

Figure 1. Images of Raw Materials

3.5 Fabrication of Advanced Composite Laminate

The fabrication of S2 glass fiber reinforced phenolic composite laminates incorporating ammonium polyphosphate (APP) was carried out using the compression moulding technique to ensure uniform consolidation and reproducibility. Prior to fabrication, the compression mould plates were thoroughly cleaned and coated with a high temperature silicone-based mould release agent to facilitate easy demoulding and prevent surface defects. The S2 glass bidirectional woven fabric (220 GSM) was cut into required dimensions using a precision cutting tool to avoid fiber fraying and misalignment. The phenolic resin was weighed accurately and mixed with 15 wt.% ammonium polyphosphate using mechanical stirring to ensure homogeneous dispersion of the flame-retardant additive within the resin matrix. The mixture was degassed under mild vacuum to remove entrapped air bubbles and minimize void formation during curing.

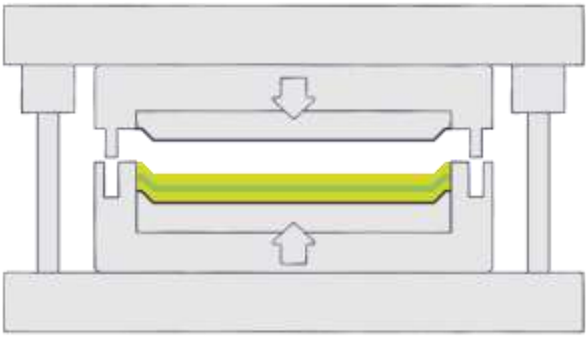


Figure 2. Compression Moulding Technique

Laminate layup was performed by stacking the pre-cut S2 glass fabric layers in a [0/90] orientation to achieve balanced in-plane mechanical properties suitable for panel applications. A total of twelve fabric plies were arranged to obtain a nominal laminate thickness of approximately 3 mm. During layup, the APP-modified phenolic resin was uniformly applied to each fabric layer using controlled manual impregnation to ensure complete wetting of the fibers. Care was taken to maintain consistent resin distribution across the laminate thickness, as non-uniform resin content can lead to resin-rich or resin-starved regions that adversely affect mechanical performance. The stacked laminate was then transferred to the compression mould cavity with suitable spacers to control the final laminate thickness.

The assembled mould was placed in a hydraulic compression moulding press, and pressure was gradually applied to facilitate resin flow, fiber impregnation, and consolidation of the laminate. Compression pressure was maintained at a predetermined level throughout the curing cycle to suppress void formation and enhance fiber–matrix interfacial bonding. The initial curing was carried out at room temperature under pressure to allow controlled resin crosslinking and to avoid excessive resin squeeze-out. This was followed by a post-curing stage at an elevated temperature of 50°C for 30 minutes, which ensured completion of the phenolic condensation reactions and improved the thermal and dimensional stability of the composite laminate.

After completion of the curing cycle, the mould was allowed to cool to room temperature under pressure before demoulding in order to minimize residual stresses and warpage. The cured laminate was carefully removed from the mould and visually inspected for surface defects, delamination, or voids. Excess edges and flash were trimmed using a diamond cutting tool, and the laminate was conditioned under ambient laboratory conditions prior to specimen preparation. Test specimens for tensile, flexural, impact, UL-94, and morphological studies were subsequently machined from the fabricated panels in accordance with relevant testing standards. The fabricated laminates obtained were uniform in thickness and exhibited good surface finish, indicating the effectiveness of the compression moulding process for producing fire-resistant composite panels.

Developed Composite Laminate

Tensile Test Specimens

Impact Test Specimens

UL94 Test Specimens

Samples for SEM Analysis

Figure 3. Developed Advanced Composite and Samples used for Testing

3.6 Material Characterization

The fabricated S2 glass fiber reinforced phenolic composite laminates containing 15 wt.% ammonium polyphosphate were subjected to comprehensive mechanical, fire, and morphological characterization to evaluate their suitability for fire-resistant panel applications. The characterization program was designed to quantify load-bearing capability, impact resistance, flame retardancy, and microstructural integrity while adhering to relevant ASTM standards to ensure repeatability and comparability of results. All specimens were prepared from compression-moulded laminates and conditioned under ambient laboratory conditions prior to testing.

Mechanical characterization included tensile, flexural, and Izod impact testing. Tensile and flexural tests were conducted using a servo-hydraulic Universal Testing Machine (UTM) with a maximum load capacity of 100 kN. The machine was operated under displacement control at a crosshead speed of 2 mm/min to ensure quasi-static loading conditions. Tensile testing was performed in accordance with ASTM D3039 using rectangular specimens with nominal dimensions of 250 mm × 25 mm × 3 mm and appropriate end tabbing to prevent grip-induced failure. Flexural behavior was evaluated following ASTM D7264 using a three-point bending configuration with a span length of 60 mm. Flexural specimens were prepared with dimensions of approximately 125 mm × 13 mm × 3 mm, ensuring a span-to-thickness ratio consistent with standard requirements. Load–displacement and stress–strain responses were recorded automatically using the machine's data acquisition system.

Impact resistance was assessed using the Izod impact test in accordance with ASTM D256, which provides insight into the material's ability to absorb energy under sudden loading. Notched specimens were prepared with standard dimensions of 63.5 mm × 12.7 mm × 3 mm, with a V-notch introduced at a specified depth to promote controlled crack initiation. The absorbed impact energy was recorded directly from the impact tester and used to evaluate the relative toughness of the composite system, particularly considering the inherently brittle nature of phenolic matrices.

Fire retardancy of the composite laminates was evaluated using the UL-94 vertical burning test, which serves as a qualitative screening method for flame resistance and self-extinguishing behavior. Specimens with dimensions of approximately 125 mm × 13 mm × 3 mm were prepared and tested under controlled conditions. The test assessed parameters such as ignition behavior, flame propagation, after-flame time, and dripping characteristics, enabling classification of the composite material based on standardized UL-94 criteria. This test was selected due to its relevance for panel-type applications requiring compliance with basic fire safety standards.

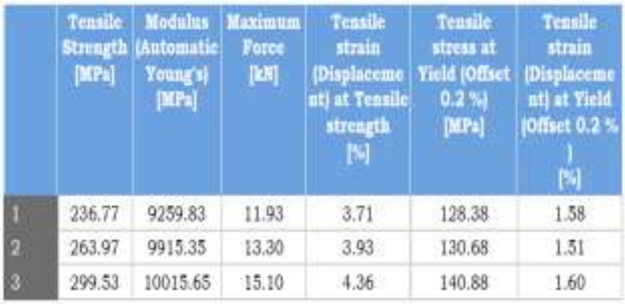
Morphological characterization was carried out using Scanning Electron Microscopy (SEM) to examine fracture surfaces from tensile and flexural tests, as well as charred surfaces after fire exposure. SEM analysis enabled detailed observation of fiber–matrix interfacial bonding, matrix cracking, fiber pull-out, and damage mechanisms governing mechanical failure. Elemental analysis and distribution of flame-retardant constituents were investigated using Energy Dispersive X-ray Spectroscopy (EDS) coupled with elemental mapping. This facilitated identification of phosphorus-rich regions within the char layer, confirming the effectiveness and dispersion of ammonium polyphosphate in promoting condensed-phase fire retardancy. SEM and EDS analyses were conducted at an accelerating voltage suitable for polymer composites to balance resolution and sample integrity.

The combined mechanical, fire, and morphological characterization framework provided a comprehensive understanding of the structure–property relationships governing the performance of S2 glass/phenolic/APP composites. The use of standardized test methods, calibrated equipment, and controlled specimen preparation ensured the reliability of the generated data and enabled meaningful interpretation of the composite's suitability for fire-resistant structural panel application.

IV. RESULTS AND DISCUSSION

4.1 Tensile Test

Table 2. Test Observations – Tensile test



	Tensile Strength [MPa]	Modulus (Automatic Young's) [MPa]	Maximum Force [kN]	Tensile strain (Displacement) at Tensile strength [%]	Tensile stress at Yield (Offset 0.2 %) [MPa]	Tensile strain (Displacement) at Yield (Offset 0.2 %) [%]
1	236.77	9259.83	11.93	3.71	128.38	1.58
2	263.97	9915.35	13.30	3.93	130.68	1.51
3	299.53	10015.65	15.10	4.36	140.88	1.60

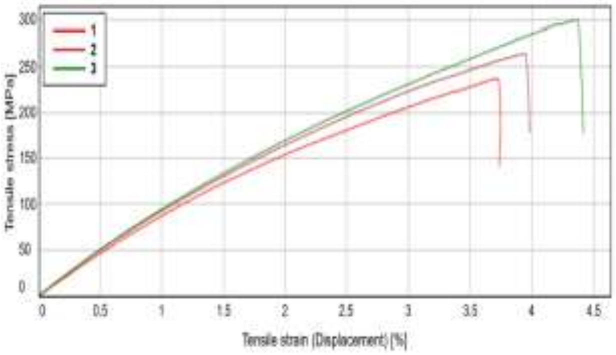


Figure 4. Stress Vs. Strain

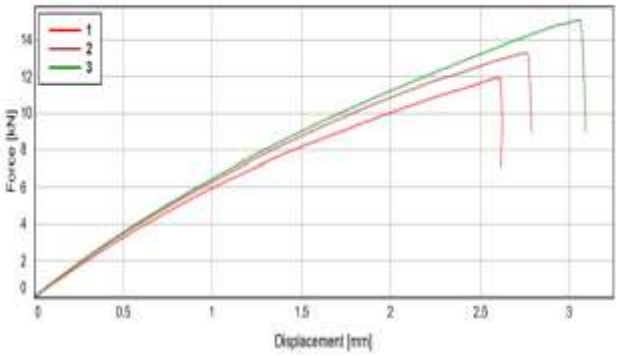


Figure 5. Force Vs. Displacement

The tensile behavior of the compression-moulded S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate (APP) was evaluated to determine its load-bearing capability and elastic response under uniaxial loading. The composite exhibited tensile strength values of 236.77 MPa, 263.97 MPa, and 299.53 MPa for the three tested specimens, demonstrating a progressive increase in strength with corresponding maximum loads ranging from 11.93 kN to 15.10 kN. This variation can be attributed to minor differences in fiber alignment, local resin distribution, and microstructural uniformity inherent to laminate fabrication. The achieved strength levels indicate effective stress transfer from the phenolic matrix to the high-strength S2 glass fibers, thereby confirming the suitability of the compression moulding process for producing structurally competent laminates despite the incorporation of particulate flame-retardant additives.

The tensile modulus values were found to be 9259.83 MPa, 9915.35 MPa, and 10015.65 MPa, reflecting relatively low scatter with an average modulus close to 10 GPa. The initial linear portion of the stress–strain curves indicates predominantly elastic behavior governed by the stiffness of the S2 glass fibers and the highly crosslinked phenolic matrix. Yield stress values determined using the 0.2% offset method ranged from 128.38 MPa to 140.88 MPa, with corresponding yield strains between 1.51% and 1.60%, signifying the onset of irreversible damage mechanisms such as matrix microcracking and fiber–matrix interfacial debonding. The consistency observed in the yield behavior among the tested specimens highlights the uniformity of laminate consolidation and effective fiber wetting achieved through compression moulding.

The composite demonstrated tensile strains at ultimate strength in the range of 3.71% to 4.36%, which is comparatively high for phenolic-based composites generally associated with brittle failure behavior. This enhanced strain capacity may be attributed to the woven S2 glass architecture, which promotes gradual damage accumulation through mechanisms such as fiber bridging and progressive matrix cracking prior to catastrophic fracture. The force–displacement response exhibited a smooth and nearly linear increase up to the peak load, followed by an abrupt drop, confirming a predominantly brittle fracture mode without evidence of premature delamination or unstable crack propagation. Overall, the tensile test results indicate that the incorporation of ammonium polyphosphate does not significantly compromise the mechanical integrity of the composite system. The combined effect of high-performance S2 glass reinforcement and effective laminate consolidation resulted in a composite suitable for fire-resistant structural panel applications.'

4.2 Flexural Test

Table 3. Test Observations – Flexural test

	Flexure stress [MPa]	Modulus (Automatic Young's) [MPa]	Maximum Force [kN]	Flexure strain (Displacement) at Yield (Offset 0.2 %) [%]	Flexure stress at Yield (Offset 0.2 %) [MPa]
1	424.34	15076.45	0.78	2.94	406.77
2	410.89	15229.23	0.74	2.69	377.93
3	432.48	15143.41	0.78	3.07	432.24

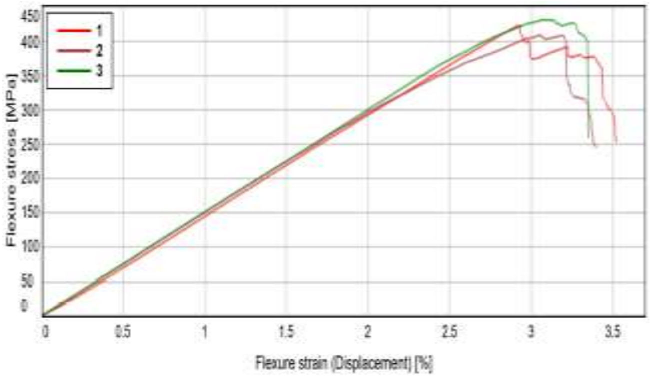


Figure 6. Stress Vs. Strain

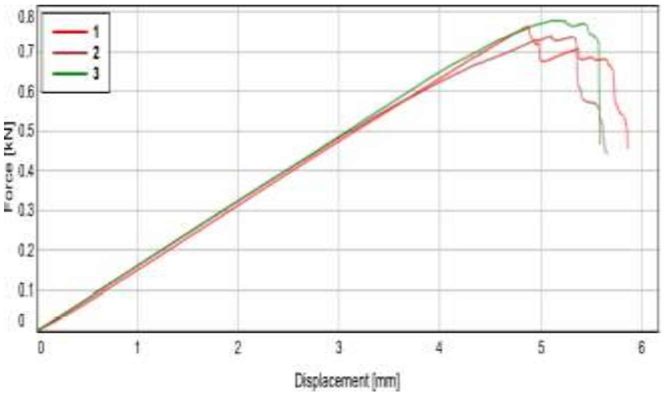


Figure 7. Force Vs. Displacement

The flexural behavior of the compression-moulded S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate (APP) was evaluated using three-point bending to assess its resistance to bending loads relevant to panel-type structural applications. The composite specimens exhibited flexural strength values of 424.34 MPa, 410.89 MPa, and 432.48 MPa, indicating a consistently high load-bearing capacity under bending. The corresponding maximum forces ranged between 0.74 kN and 0.78 kN, confirming stable structural response with limited scatter among specimens. The high flexural strength achieved highlights the effectiveness of the woven S2 glass reinforcement in resisting tensile stresses on the bottom surface and compressive stresses on the top surface of the laminate during bending.

The flexural modulus values obtained were 15076.45 MPa, 15229.23 MPa, and 15143.41 MPa, demonstrating excellent stiffness with minimal variation across specimens. This uniformity reflects effective laminate consolidation, consistent fiber volume fraction, and strong fiber–matrix adhesion achieved through compression moulding. The initial linear region of the flexural stress–strain curves (Figure 6) confirms elastic deformation dominated by the glass fiber reinforcement and the crosslinked phenolic matrix. Yield stress values determined using the 0.2% offset method ranged from 377.93 MPa to 432.24 MPa, with corresponding yield strains between 2.69% and 3.07%, indicating delayed damage initiation compared to tensile loading due to the stress gradient inherent in flexural deformation.

The force–displacement response (Figure 7) exhibited a smooth and nearly linear increase in load with displacement up to peak force, followed by a sudden drop associated with fracture. This behavior is characteristic of glass fiber reinforced phenolic composites and suggests a predominantly brittle failure mode governed by tensile fracture of fibers on the tension side and localized matrix cracking. The absence of abrupt load fluctuations prior to failure indicates limited delamination and good interlaminar integrity. Overall, the flexural results demonstrate that the inclusion of ammonium polyphosphate does not significantly degrade bending performance, while the combined effects of high-strength S2 glass fibers, phenolic matrix, and effective consolidation yield a composite system well suited for fire-resistant structural panel applications subjected to bending loads.

4.3 Impact Test

The impact resistance of the compression-moulded S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate (APP) was evaluated using the Charpy impact test to assess its ability to absorb energy under sudden loading conditions. The measured impact energy absorption values for the three specimens were 15 J, 13 J, and 15 J, respectively. These results indicate a reasonably consistent impact response with narrow variation between specimens, suggesting uniform laminate quality and effective fiber distribution. The slightly lower energy absorption observed for specimen 2 can be attributed to localized microstructural variations such as minor differences in resin distribution, fiber alignment, or the presence of micro-voids, which are typical in particulate-filled thermosetting composites.

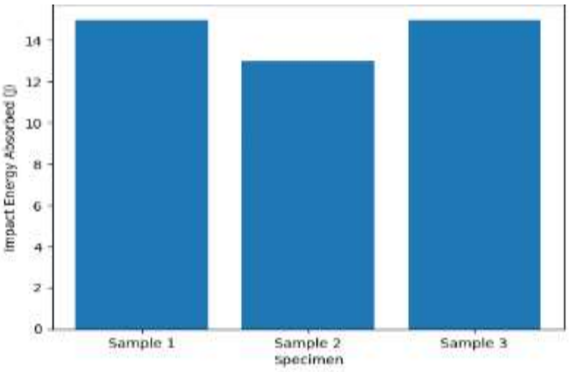


Figure 8. Energy Absorption behaviour of the Samples

The overall impact energy levels demonstrate that the composite retains moderate toughness despite the inherently brittle nature of phenolic matrices and the incorporation of ammonium polyphosphate. Energy absorption during impact is primarily governed by damage mechanisms such as matrix cracking, fiber fracture, and limited fiber pull-out, while the woven S2 glass architecture contributes to crack deflection and stress redistribution. The presence of APP does not appear to severely embrittle the composite, indicating good dispersion within the phenolic matrix and minimal formation of critical stress concentrators. These results confirm that the developed S2 glass/phenolic/APP composite possesses sufficient impact resistance for fire-resistant panel applications where resistance to accidental or low-velocity impact loading is required in addition to mechanical strength and fire safety.

4.4 UL94 Test

The flame retardancy of the compression-moulded S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate (APP) was evaluated using UL-94 vertical and horizontal burning tests to assess its resistance to ignition, flame propagation, and dripping behavior. The UL-94 test provides a qualitative yet critical screening method for fire performance of polymeric materials intended for structural and panel applications. Key parameters such as burning time, burned length, and dripping characteristics were recorded to understand the effectiveness of the phenolic–APP system in suppressing flame spread and maintaining structural integrity during exposure to open flame.

Table 4. UL94 Vertical Testing

S. No	Sample Code	Time (S)	Burnt length (mm)	Dripping
Set 1-SGlass+APP				
1	Sample 1	195	15	No Dripping Occurs
2	Sample 2	143	9	
3	Sample 3	159	21	

Table 5. UL94 Horizontal Testing

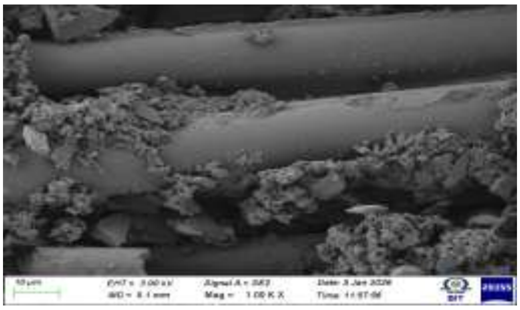
S. No	Sample Code	Time (S)	Burnt length (mm)	Dripping
Set 1- SGlass+APP				
1	Sample 1	125	14	No Dripping Occurs
2	Sample 2	86	11	
3	Sample 3	73	8	

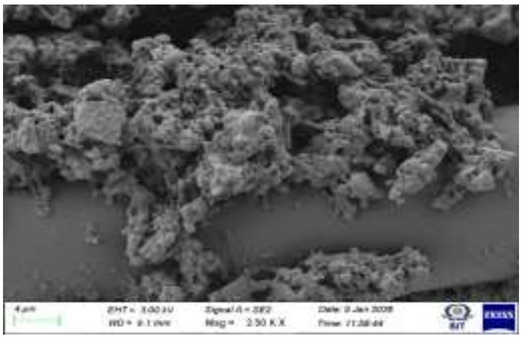
In the UL-94 vertical burning test, the specimens exhibited burning times of 195 s, 143 s, and 159 s, with corresponding burned lengths of 15 mm, 9 mm, and 21 mm for samples 1, 2, and 3, respectively. Importantly, no dripping was observed for any specimen, indicating excellent melt stability and condensed-phase flame-retardant action. The relatively short burned lengths and self-sustaining char formation suggest that the combined effect of phenolic resin and APP effectively limits downward flame propagation. The variation in burning time and burned length among specimens can be attributed to localized differences in resin distribution, APP dispersion, and char layer thickness, which influence heat transfer and oxygen diffusion during combustion. Nevertheless, the absence of dripping and controlled burn behavior across all specimens demonstrates a stable and reproducible fire response.

The UL-94 horizontal burning test further confirmed the flame-retardant efficiency of the composite system. The recorded burning times ranged from 73 s to 125 s, with burned lengths of 8 mm to 14 mm, again with no dripping observed. Compared to vertical testing, the reduced burned lengths and shorter burning times indicate effective flame suppression under horizontal orientation, where gravity-assisted flame spread is minimized. The superior performance in horizontal testing highlights the role of APP-induced intumescence, which leads to the formation of a protective, expanded char layer that insulates the underlying composite from heat and oxygen. Overall, the UL-94 test results demonstrate that the developed S2 glass/phenolic/APP composite exhibits reliable flame-retardant behavior with negligible dripping and controlled burn characteristics, making it suitable for fire-resistant panel applications in safety-critical engineering environments.

4.5 SEM Analysis of the Samples before Mechanical Testing

The scanning electron microscopic (SEM) images of the S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate, acquired prior to mechanical fracture, provide valuable insight into the surface morphology and microstructural integrity of the fabricated laminate. The low-magnification micrograph reveals a relatively uniform and continuous matrix surface with no evidence of macro-voids or severe resin-rich regions, indicating effective consolidation during compression moulding. The phenolic matrix appears well bonded to the surrounding reinforcement, with limited surface discontinuities, suggesting adequate resin flow and impregnation despite the presence of particulate APP. The absence of large cracks or interfacial debonding features in the pre-fracture state confirms that the laminate was structurally intact prior to mechanical loading.





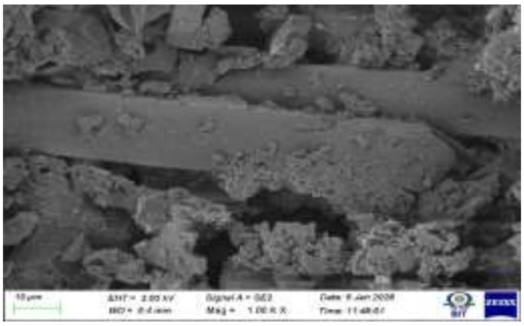


Figure 10. Scanning Electron Microscopic images of the samples after Fracture

Higher-magnification SEM observations further reveal a finely textured matrix morphology with embedded particulate features attributed to ammonium polyphosphate dispersed within the phenolic resin. These particles are uniformly distributed and appear well integrated into the matrix, with no significant agglomeration observed at the microscale. Such homogeneous dispersion is critical in preventing localized stress concentration sites that could otherwise lead to premature failure. The microstructural continuity observed in these images supports the mechanical test results, where consistent tensile and flexural properties were recorded across specimens. Overall, the SEM analysis before fracture confirms that the compression moulding process produced a dense, well-consolidated composite with strong fiber–matrix interaction and stable flame-retardant additive distribution, thereby providing a sound microstructural basis for the observed mechanical performance.

4.7 Energy Dispersive X-ray Spectroscopy (EDS) Analysis

Energy Dispersive X-ray Spectroscopy (EDS) was employed to investigate the elemental composition of the S2 glass fiber reinforced phenolic composite containing 15 wt.% ammonium polyphosphate (APP) and to confirm the presence and distribution of flame-retardant constituents within the matrix system. The EDS spectrum obtained from the analyzed surface region indicates the presence of major elements such as carbon (C) and oxygen (O), which are characteristic of the phenolic resin matrix, along with silicon (Si) originating from the S2 glass fibers. Additionally, the detection of phosphorus (P) confirms the successful incorporation of ammonium polyphosphate into the composite system. The absence of unexpected elemental peaks suggests that the composite fabrication process did not introduce contaminants and that the material composition is consistent with the intended formulation.

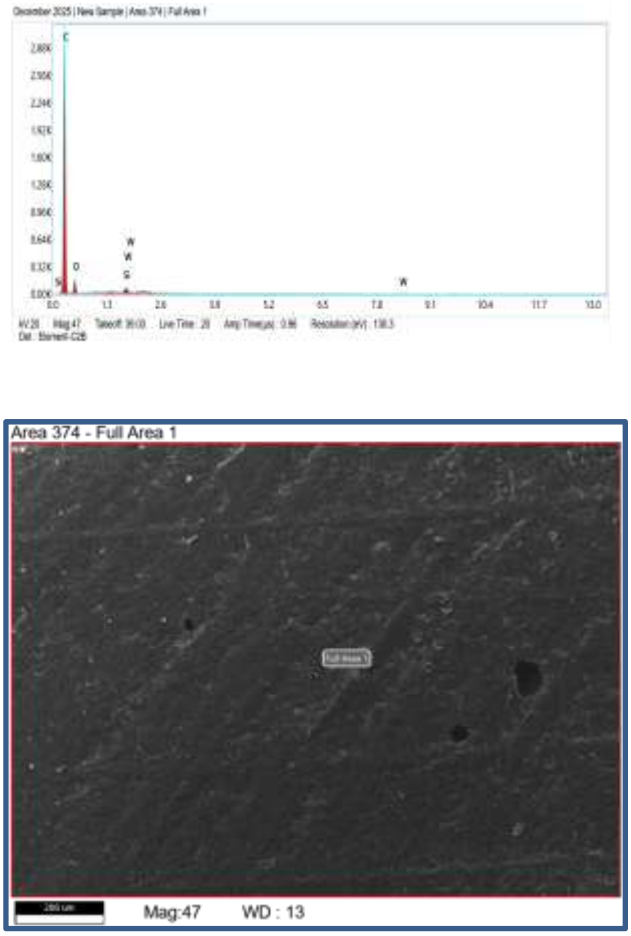


Figure 11. EDS Alalysis of the Samples

The spatially resolved EDS analysis over the selected SEM area reveals a relatively uniform elemental distribution, indicating effective dispersion of APP within the phenolic matrix. The homogeneous presence of phosphorus across the analysed region suggests that APP is well integrated and not localized into isolated agglomerates, which is critical for ensuring consistent flame-retardant behavior throughout the composite. This uniform distribution supports the UL-94 fire test results, where controlled burning and absence of dripping were observed. Furthermore, the coexistence of phosphorus with carbon-rich regions provides indirect evidence of the condensed-phase flame-retardant mechanism, wherein APP promotes char formation during thermal exposure. Overall, the EDS analysis confirms the compositional integrity of the developed composite and substantiates the role of ammonium polyphosphate in enhancing fire resistance without adversely affecting microstructural uniformity.

V. CONCLUSION

The present investigation successfully demonstrated the fabrication and characterization of a fire-resistant S2 glass fiber reinforced phenolic composite incorporating 15 wt.% ammonium polyphosphate using the compression moulding technique. The fabrication process produced well-consolidated laminates with uniform thickness and minimal defects, as confirmed through pre-fracture SEM analysis. Mechanical characterization revealed that the composite exhibited high tensile strength (up to ~300 MPa) and flexural strength exceeding 430 MPa, accompanied by consistent elastic moduli under both loading conditions. The tensile and flexural responses indicated effective stress transfer between the S2 glass fibers and the phenolic matrix, while the woven fabric architecture enabled moderate strain tolerance prior to failure. Charpy impact testing further demonstrated that the composite retained reasonable energy absorption capability (13–15 J), confirming that the inclusion of ammonium polyphosphate did not significantly embrittle the system despite the inherently brittle nature of phenolic resins.

Fire performance evaluation using UL-94 vertical and horizontal burning tests confirmed the effectiveness of the phenolic–APP system in suppressing flame propagation, with limited burn lengths, controlled burning times, and complete absence of dripping across all specimens. Post-fracture SEM analysis revealed failure dominated by matrix cracking and fiber fracture with limited fiber pull-out, indicating strong fiber–matrix interfacial adhesion. EDS analysis further validated the homogeneous distribution of phosphorus from ammonium polyphosphate within the composite, supporting its role in promoting condensed-phase char formation and enhanced fire resistance. Collectively, the results establish that the developed S2 glass/phenolic/APP composite achieves a favourable balance between mechanical integrity and flame retardancy, making it a promising candidate for fire-resistant structural panel applications in safety-critical engineering environments.

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