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Research Article

Sustainable Recycled Cotton Fabric and Clay Powder Composites for Improved Thermal and Mechanical Performance in Home Furniture

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clay powder
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ABSTRACT

The rapid growth of non-degradable plastics with poor management of waste is a major international challenge for the environment; thus, prompt development of high-performance sustainable materials is demanded. In this work, the epoxy-based composites reinforced by waste cotton fabric and clay powder were developed to improve mechanical and thermal properties for home furniture. The impacts of different cotton fabric content and clay powder loading on tensile strength, flexural strength, impact resistance, and thermal conductivity were systematically investigated. The results show that the addition of waste cotton fabric leads to a marked improvement in the mechanical properties with an efficient load transfer and stress distribution. The addition of clay powder also improves strength, stiffness, thermal stability, and flame retardancy. Tensile strength and impact strength increased from 12.5 MPa to 24.7 MPa and from 2.3 kJ/m² to 4.5 kJ/m², respectively, for materials with an optimal composition of 30 g cotton/3% clay powder component percentage ratio. For heat dissipation, thermal conductivities were from 0.12 to 0.28 W/m·K. With a medium content of clay (3%), better composite bonding and thermal properties were achieved, while high loadings (5%) resulted in agglomeration, thereby degrading the composite. These results indicate that recycled cotton fabric and clay powder have potential as eco-friendly reinforcements for sustainable, durable, and thermally insulating furniture material.

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1. Introduction

Composite materials have revolutionized modern engineering and fabrication as a result of their unique capability to integrate the properties of two or more different materials into new performance-enhancing products [1-4] Typically, these materials contain a reinforcement and matrix such as epoxy resin [1-4]. Being combined, these are providing better mechanical, thermal, and chemical properties over conventional fibers or fillers. There are many benefits of composite materials for home furnishing, such as weight reduction, resistance to environmental factors (such as moisture and thermal variation), and durability over time. Due to its excellent bonding strength, chemical resistance, and mechanical properties, epoxy resin is one of the widely used matrix materials for composites [1-4]. The growing demand for green and sustainable materials has accelerated the design of natural fiber/bio-based filler composites, such as recycled cotton fabric and clay powder. This transformation provides a viable approach to producing high-quality, green furniture materials and is in line with global sustainable development goals [1-4].

In the digital age of convenience where technology has simplified countless tasks, a home furniture application stands as an epitome of efficiency, resourcefulness for users who wish to experience furnishing and decorating personal space [5,6]. In parallel, within the dynamic market of the furniture industry, custom properties of epoxy resin have become a focus of attention with growing demand for materials used in producing furniture which can offer durability and non-toxic attributes as well as economic benefits [5,6]. In fact, it is the combination of durability, environmentally friendliness and cost-effectiveness that makes epoxy resin most desirable to consumers and producers [7-9]. Nevertheless, features such as high strength and resistance to chemicals make epoxy resin a very good candidate of the material for home furniture use, but the limitations in mechanical and thermal properties should be considered re-grading its appliance in particular environment or forms [7-9].

An opportunity arises, however, to investigate the use of different materials, and specifically in utilizing waste fabrics which are produced during the process of creating furniture [9-12]. Waste fabrics Defective fabric the waste fabric as an effective reinforcement can enhance mechanical properties Waste management, an environmentally solution preventing waste from going into landfills, typical defective (waste) woolens in wool industry Department Field (dye house). So far in the literature, with respect to combined effects of waste fabric reinforcement, and clay powder, on epoxy resin developed for home furniture application this aspect has not yet been investigated [9-12]. Therefore, the purpose of this study is to close this gap by examining the effects of waste fabric reinforcement and clay powder reinforcements on the mechanical and thermal characteristics of epoxy resin-based composites. This research aims to contribute to the development of high-performance, sustainable materials suited for home furniture while promoting circular economy and environmental responsibility through waste reduction and repurposing.

2. Litreatures

2.1. Introduction to Composite Materials

Nature contains composites. Wood is a composite material composed of long cellulose fibers and lignin. Material composites formed by combining two or more constituent materials with significantly dissimilar chemical or physical properties are denominated composite materials [13-16]. As opposed to combining the involute spurs, these ingredients are separated by man-made boundaries in the final texture and act cooperatively to even more efficiently perform mechanical, thermal and/or chemical tasks [13-16]. Fundamentally, a composite contains three parts. One is the matrix serves as the continuous phase to bond and shelter the reinforcement against mechanical damage and harsh environments [13-16]. The second ingredient is a reinforcement that forms the discontinuous or dispersed phase and takes the form of generally fibers or particles. The main purpose of this phase is to enhance mechanical properties of the composite, such as strength and rigidity [13-16]. The third component is the interphase, occasionally called the interface. That is the layer which separates the matrix and reinforcement. The role of this region in stress transmission and the interfacial bonding between the two constituent phases, makes it important when considering the overall performance of a composite. Composites [13-16] Composites are typically composed of a matrix (polymer, metal or ceramic) into which is added a reinforcing phase (such as fibers or particles) that increases strength and stiffness. As of their excellent strength-to-weight ratio, resistance to corrosion, and adaptability in design, composites are frequently used in sports equipment, automotive, aerospace, and construction. Textile waste materials and natural fiber-reinforced composites have also drawn interest as environmentally friendly and resource-renewable substitutes for synthetic materials [13-16]. A detailed explanation of each component is provided in the following sections.

2.2. Reinforcement of Materials in Composites

Reinforcement phase Factors that play important roles in determining mechanical, thermal properties of the (composite) material, are the reinforcement materials [17]. Among the natural fibers, hemp, flax, jute and cotton have gained considerable interest as environmentally friendly alternatives of synthetic reinforcements (carbon or glass) [18]. Among them, waste cotton fabric is a promising choice because of its abundant, low cost and environmental friendly. Cotton fibers have tensile modulus, flexibility and biodegradability to be used as a reinforcing material for epoxy matrices [19]. Woven fabrics of cotton in composites are consistent with the circular economic principles and efficient resource conservation; thus, we identify them as a new option for covering home textile and other fields [20].

2.3. Clay Powder Fillers in Composite Materials

Tona fillers are necessary ingredients for the composites, which are usually used to improve certain properties such as cost effectiveness, mechanical strength, flame retardance and thermal stability [21]. These inorganic and organic materials are added into the matrix to alter the properties of the composite without increasing weight appreciably [21]. Of several fillers, clay powders, such as kaolin and montmorillonite, have been increasingly used with respect to their availability in nature, cost-effectiveness, and the fact that they can enhance both mechanical and thermal performance [22]. In epoxy resins composites, the clay powder enhances thermally stability due to its heat barrier effect that lowers its susceptibility to high temperature. Furthermore, interaction between polymer chains and clay leads to mechanical enhancements including enhanced tensile strength, improved impact resistance and stiffness through the formation of a dense and rigid network in the matrix [23]. Another promising property of the clay powder is that it has an inherently flame-retardant nature, which is beneficial for applications within household furniture due to frequent fire hazardous problems [24]. One type of clay, known for its high surface area and swelling properties, is found in colors ranging from white to pale yellow, green, blue or red. These variations in colour are mainly dependent upon impurities, hydration levels and mineral content. This type of clay has attracted attentions as polymer nanocomposite reinforcing agents because of its peculiar structure and properties [25]. In this study, kaolin clay was selected as the reinforcement since its reinforcing performance could reach our requirement and it had low cost.

2.4. Waste Fabric

Waste clothing refers to the fabrics that are no longer intended for their initial purposes and to be discarded, or being treated as rubbish [26]. This comprises textiles of different materials, such as cotton, polyester, nylon and wool including mixtures thereof [26]. The waste fabric comes from a variety of sources: manufacturing scraps, off-cuts from clothing manufacture, used clothes and household linens. Various kinds of waste fabric, in field applications are investigated for their mechanical, thermal and morphological behavior a [26].

Cotton Fabric: Cotton fabric scraps are easily obtainable and have great adhesion to epoxy resin. It has an acceptable strength and stiffness and it is indicated for applications requiring a lightweight reinforcement such as for hybridizations [26,27].

Polyester Cloth: The wasted polyester cloth is high in tensile strength, wear-resistant and durable. Such ENR is frequently used as a reinforcement in epoxy composites that require improved mechanical properties [26,28].

Nylon Fabric: Nylon fabric offcuts are highly durable, tough and elastic. It has good impact strength and toughness as a reinforcing filler in epoxy resin matrices [26,28].

Cotton-Polyester blended: A synthetic fiber blend, PC (commonly referred to as poly-cotton) is 60% polyester and 40% cotton. It possesses the natural comfort of cotton and the weather tolerance, fabric strength and rigidity of polyester [26,29].

2.5. Epoxy Resin in Composite Manufacturing and Furniture Applications

Due to their excellent mechanical, thermal and chemical properties [30], epoxy resins are considered as one of the most extensively used matrix materials for composites applied in industrial manufacturing. Epoxy is a highly-strength adhesive material that features high tensile strength and resistance to environmental damage making it favorable for household furniture [30,31]. It could also have strong adhesion with reinforcing materials, such as fibers and fillers30-32), which is an important criterion to fabricate high-performance composites. Nevertheless, epoxy in its pristine form has some shortcomings or limitations, such as brittleness, low impact resistance, and poor thermal conductivity that may confine its application to more demanding sections [32]. In addition, the epoxy composites are easily formed into complex shapes, allowing design freedom for today's furniture uses. When combining and using epoxy together with sustainable reinforcements as well as fillers, eco-friendly composites are obtained which fulfill the performance and environmental demands and open door for new solutions already in furniture industry [33].

Epoxy adhesives are of high importance in household furniture because they serve a dual purpose of holding the structure together and having a pleasing appearance. An epoxy (such as epoxy resins) is a thermosetting polymer with good strength, durability and environmental resistance that makes it suitable for furniture generation [34]. its broad material compatibility; the possibility of creative design, which may enable its integration in contemporary furniture (C) [30]. Furthermore, its resistance against chemicals and moisture as well as temperature variations guarantees stability in indoor and outdoor conditions [34-37]. Epoxy as well improves the aesthetics of furniture in terms of gloss which enhances more sophistication to its functional properties [34-37]. In short, in addition to its form and function integration role played in home furniture application, epoxy resin also helps turn out the stylish-looking furniture with high durableness used to embellish living place [34-37]. It is necessary to know the thermal and mechanical properties of epoxy resin based composite in order to improve their application for furniture manufacturing [34-37]. On the one hand, understanding of these properties will facilitate manufacturers to choose suitable epoxy formulations and reinforcements (e.g., clay powder and waste fabric) from variety choices to conform requirements of applications [33-37]. For instance, knowledge of thermal conductivity and heat resistance is required for the design of furniture that can sustain temperature fluctuations without warping or deteriorating [33-37]. Second, knowledge in mechanical properties including tensile strength, flexural modulus and impact resistance becomes a prerequisite to maintain the structural stability of furniture [33-37]. This is particularly important for components that are regularly used or heavily loaded [33-37]. In summary, the fundamental knowledge on thermal and mechanical processing performance of epoxy resin composites is constructive for producing furniture with high durability, functionality and aesthetic design that can meet both consumer demands and sustainable ambitions.

2.6. Hybrid Composites

A new generation of composite materials known as hybrid composites is a class of advanced material in which two or more different types of reinforcements or fillers that serve the useful purpose are combined into one single matrix so that synergistic effects and properties can be realized [36,37]. Hybrid composites, by combining various materials such as natural fibers (waste cotton fabric) and inorganic fillers (clay powder), are able to take the merits of each constituent with reduced deficiencies [36,37]. For instance, cotton waste cloth provides flexibility, biodegradability and economical cost in the composite, whereas clay powder improves thermal stability, mechanical properties and flame resistance [of the composites]. Once incorporated in an epoxy matrix these materials generated a composite with balanced properties, making it a good candidate for challenging applications such as home furniture [36,37]. The hybridization also gives the opportunity to tailor properties such as tensile strength, impact resistance, thermal conductivity, and general durability which are important in functional long-lasting furniture materials [36,37]. It is also because the interaction among different elements contributes to load transmission and stress dispersion in the matrix, which makes the performances of hybrid composites better than those with single reinforcement. The appropriate design and proportioning of reinforcement and filler play an important role in the structural performance properties of hybrid composites [36,37]. This design approach not just improves mechanical and thermal properties, but it is also in congruence with sustainable goals with the use of renewable and waste-based resources [36,37]. Hence, hybrid composites have been emerging as a new application in furniture industry as alternative to typical used materials with better strength, durability and environmental advantages [36,37].

3. Material and Methodology

3.1. Materials

Waste Fabric*:* Fabric waste was gathered from different places in Addis Ababa, Ethiopia: textile industries, tailor shops, and houses. They were used as eco-waste less than reinforcement materials. Epoxy composites incorporating waste cotton fabric have improved tensile strength, impact resistance, and toughness and is a sustainable, cost-effective reinforcement for furniture applications at home.

China clay, also known as kaolin clay: is a fine-grained white clay comprising mainly of kaolinite. It is used in a number of industries owing to its malleable nature and whiteness. But in color it varies from pure white to light gray or cream, according as the impurities and minerals that accompany it are more or less abundant.

Resin and Hardener (3:1 ratio): A thermosetting polymer that dries up quickly due to its good adhesive strength and high mechanical properties in addition to resistance to chemicals and hard wearing. It has been widely used in coatings, adhesives, composites, and reinforcement materials with high abrasion levels (such reinforced composites as clay powder or waste cotton fabric) for improved thermal and mechanical properties for home furniture.

MDF (Medium Density Fiberboard): This is an engineered wood made out of wood waste such as fibers, resin, and wax, which are pressed using high-temperature application and pressure. It is also a common material used in the furniture industry for its surface, which is easy to sand and lacquer at low cost; it resists warping. MDF is, however, not as durable to moisture and mechanical stress as solid wood; therefore, better durability than manufactured fiberboard can be achieved by reinforcement with materials such as epoxy composites along with clay powder and waste cotton fabric, also improving thermal stability [38].

Amylase enzyme*:* Amylase is an enzyme that metabolizes starch into smaller sugars such as maltose and glucose. It is produced by plants, animals and micro-organisms: it plays an extremely important role in digestion, fermentation and other industrial purposes [39]. In the industry, amylase is used to efficient starch-hydrolyzing activity of starches in various applications like food processing, textile de-sizing, paper production and bio-fuel manufacturing [39].

3.2. Methodology

Figure 1 and Figure 2 demonstrate that one gram of starch was dissolved in 100 mL distilled water to obtain a 1% starch solution. After the solution have been boiled, it was left to cool down to room temperature to ensured total dissolution of the solubilizer. Cotton waste was cut into small pieces with accurate weighing. These fabrics samples were placed in the enzyme solution, heave then warm at around 50–60 °C for a certain period of time, from 2 to maximum of 6 h. The solution was agitated intermittently during incubation to allow even distribution of enzyme activity throughout the fabric. After the treatment, fabric was thoroughly washed with distilled water to eliminate any excess enzyme or starch. The washed fabric was subsequently spread out for drying at room temperature or in an oven at very low heat (40–50°C) and hand-mechanically treated, as well as with rubbing the soaked fabric on a flat surface, to generate mechanical forces, releasing the fibers from the fabric weave.

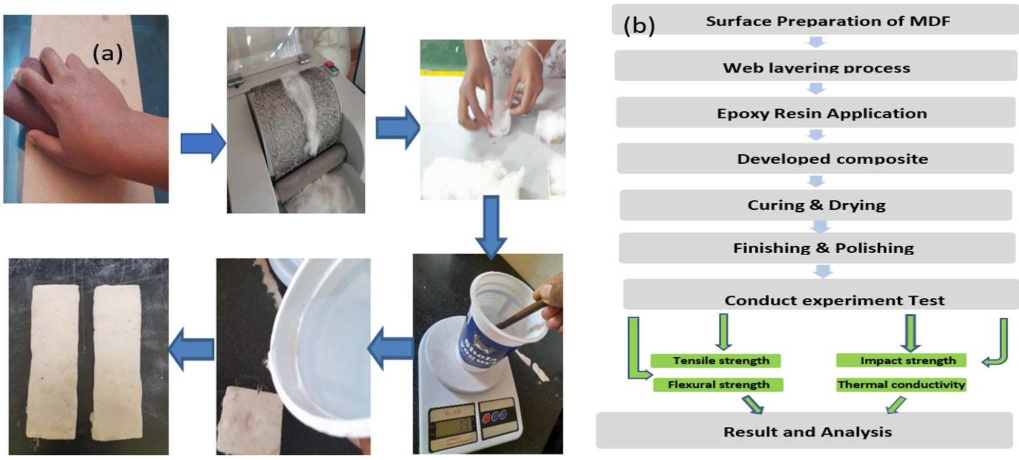

Figure 1. Experimental Procedure: a) Lamination and b) Flow Chart of Experimental Procedures

Surface Preparation of MDF: Before starting any process with the electroplating or decoration with chrome, clean down the surface to ensure that there is no excess dust on the product. Then sanding is carried out to enhance the roughness of the surface so as to provide a fitter with which for the fiber web adheres. In addition, for bonding the MDF to the non-woven web an optional primer or adhesive layer is used producing an effective interface between the MDF and the NW.

Preparation of non-woven fiber web: The degraded cotton fibers were also mechanically separated to prepare a paper sheet, which would eventually become non-woven web. It is laid on top of the MDF surface, featuring recycled cotton fabric. The web may be randomly or directionally oriented, depending on the desired strength and flexibility for the resulting composite. Cavities are preferably compressed with a roll or vacuum press, which dissipates any voids and bonds the fiber layer. *Epoxy resin mixture:* Epoxy resin mixture: Containing hardener and clay powder filler, it is evenly applied over the fiber web without agglomeration. This occurs when fine clay powder particles stick together instead of dispersing evenly in the epoxy resin. This leads to the formation of brittle zones, resulting in uneven load distribution and a decline in both thermal and mechanical properties of the composite. To prevent this issue, techniques such as mechanical stirring and sonication to enhance clay dispersion ensure a uniform and strong composite structure. The resin is carefully distributed using a brush, roller, or spray coating method. Efficient resin infiltration minimizes the formation of dead spots and ensures uniform adhesion. When fully saturated, the treated web of resin is deposited onto the substrate of MDF and subjected to controlled pressure while it cures and develops a strong and durable composite part.

Hand Lay-Up Process: Web layering process entails the placing of a non-woven fiber web of reclaimed cotton cloth onto the surface of the MDF with careful attention. Web alignment can be either directional or of a random nature depending on the required mechanical properties. Air pockets are eliminated and the fiber layer firmly fixed onto the MDF with a roller or vacuum press for good adhesion and distribution.

Curing & Drying: Curing and drying procedures involve placing the stacked MDF under room conditions for a period of 24 to 48 hours, allowing the resin to continue hardening and enabling proper adhesion. For an acceleration of the curing process, the composite could be exposed to an oven condition at temperatures of 60 to 80°C and thus induce quick hardening and an improved mechanical quality of the resulting material.

Preparation of Test Samples of Mechanical Properties: Test specimen dimensions of each respective test are determined as per guidelines of standard test protocols laid out (for example, as per ASTM standards). For the sake of the predetermined ratios of cotton waste fabric and clay powder, the specimen dimensions are tabulated in Table 1. For increasing the reliability of the results of experiments, statistical methods (Taguchi method and ANOVA or Analysis of Variance) were used.

Table 1: Mechanical Test and their Test Standards

Mechanical Properties Test	Test Standard	Sample Dimensions	Reference
Tensile Strength Test	ASTM D638	165 mm × 13 mm	[40]
Flexural Strength Test	ASTM D790	127 mm × 12.7 mm	[41,42]
Impact Strength Test(Izod)	ASTM D256	63.5 mm × 12.7 mm	[43]

Differential Scanning Calorimeter (DSC): Used to determine several thermal properties of a material such as glass transition point, melting temperature and the heat of reaction. In the context of cotton fabric and clay powder composite with epoxy intended for home furniture use, DSC is instrumental in establishing heat flow parameters. The thermal conductivity (W/m·K) results in your study indicate that increasing cotton and clay content affects structural integrity, which means the material is more energy efficient.

4. Result and Discussion

4.1. Tensile Strength of Waste Cotton-Clay Powder Laminate Composite

Figure 2 displays the tensile strength outcomes across the various experimental runs, illustrating how different amounts of cotton waste fabric and clay powder impact the composite's tensile strength. There's a clear increase in tensile strength as the cotton waste fabric content goes up, peaking notably at 30 g. On the other hand, the data for clay powder seem less consistent, tensile strength shows only minor variations at each cotton level, with no obvious upward or downward pattern. This means that cotton waste fabric really functions as the principal reinforcement, providing significant mechanical improvements. Meanwhile, adding more clay powder past an optimal point barely changes things, signaling a kind of saturation in its strengthening effect. To sum it up, Figure 2 illustrates these patterns, and the regression model for tensile strength supports the observed relationships between the materials and the composite's strength.

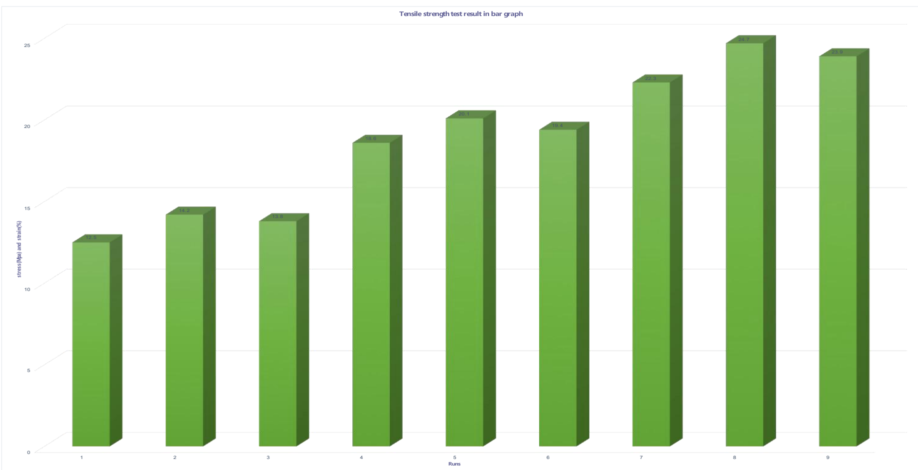

Figure 2. Tensile Strength Test Result

Regression Equation for Tensile Strength:

$$\text{Tensile Strength(MPa)} = 8.67 + 0.2200\ \text{Waste Cotton Fabric (g)} + 0.270\ \text{Clay Powder (\%)} + 0.01000\ \text{Waste Cotton Fabric (g)*Clay Powder (\%)}$$

Using variance analysis (ANOVA), researchers gauged the relative importance of each component based on its percentage in the reaction. ANOVA serves as a crucial tool for predicting errors and establishing confidence intervals for the special effect error variance. When it comes to determining likelihood, factors like degrees of freedom and P-values come into play. Adj MS (adjusted mean square) and Adj SS (adjusted sum of squares) show up to give a clear sense of how much each factor contributes, once everything's balanced out. The F-value, reported at a 95% confidence level, is shown in the table for clarity.

Table 2. Analysis of Variance of Tensile Strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.056432	0.018811	9.42	0.015 (Significant)
Linear	2	0.0521	0.02605	12.34	0.007 (Significant)
Waste cotton fabric(g)	1	0.02845	0.02845	14.67	0.005 (Significant)
Clay powder (%)	1	0.02365	0.02365	12.19	0.008 (Significant)

In Table 2, the ANOVA results indicate that the model is statistically significant (P = 0.015, F = 9.42), meaning the chosen components have a meaningful effect on the response variable. Overall, the ANOVA checks out, the factors are closely tied to the response. Notably, tweaking the significance threshold shows that waste cotton fabric exerts a slightly greater influence in the linear regression than clay powder. That being said, clay powder showed fewer significant effects versus other samples (still, it did manage a P-value of 0.005 and F of 12.19).

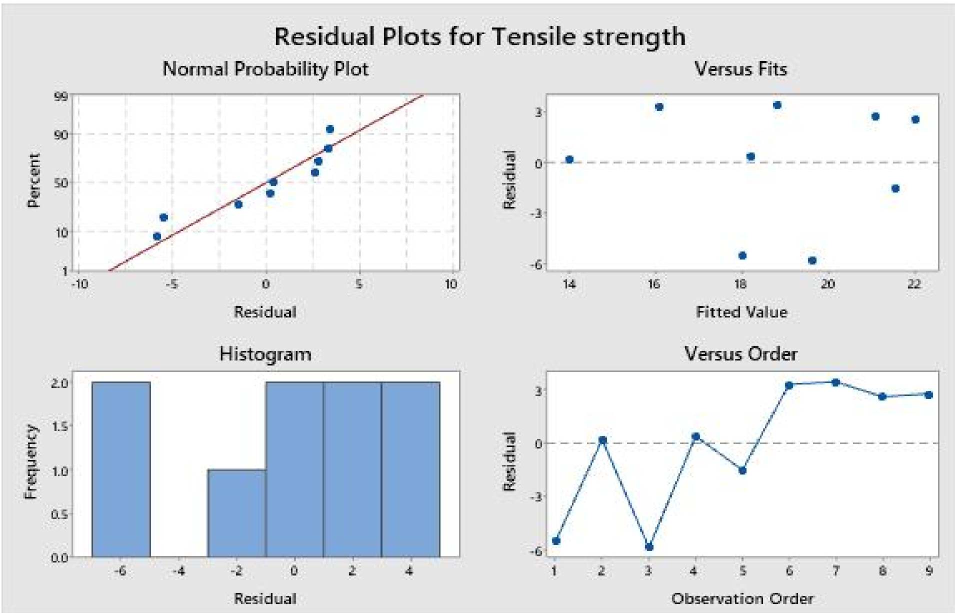

Figure 3. Residual Plots for Tensile Strength.

For tensile strength, residual diagnostics, normal probability, histogram, versus Fits, and Versus Order plots, were used to check model assumptions. Both the Normal Probability Plot and Histogram supported that the residuals were approximately normal and didn't stray from expected patterns (see Figure 3). The Versus Fits plot suggested homoscedasticity and linearity, with residuals scattered randomly around zero. Meanwhile, the

Versus Order plot didn't show any autocorrelation or patterns over time. Together, these results confirm the model's assumptions hold, which strengthens the reliability and validity of the statistical analysis presented.

4.2.Flexural Strength Analysis

Flexural strength of the composite specimens was assessed using the three-point bending method on a Universal Testing Machine (UTM). Results demonstrate that increasing cotton waste fabric content significantly enhances flexural strength, reaching a maximum of 26.5 MPa at 30 g cotton and 3% clay powder. While moderate clay powder loading (3%) further improves flexural performance, higher content (5%) induces a slight strength reduction, likely due to particle agglomeration. These trends are summarized in Figure 4, which presents flexural strength as a function of the experimental runs.

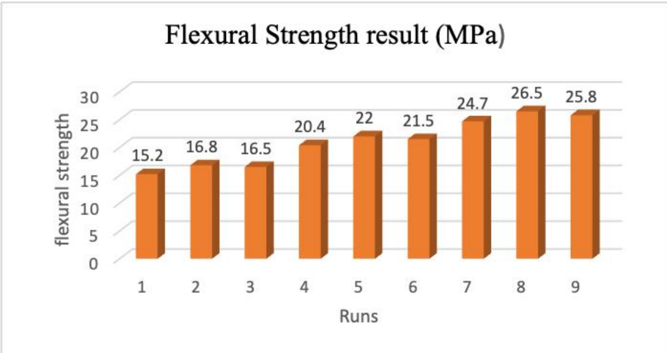

Figure 4: Flexural Strength of Test Result.

The bar graph presents the effects of varying cotton waste fabric and clay powder content on the composite's flexural strength. Evidently, increasing cotton content from 10g to 30g leads to a notable improvement in flexural strength, which indicates that cotton fabric offers substantial reinforcement for the epoxy matrix. The optimal flexural strength, measured at 26.5 MPa, occurs when the composition contains 30g of cotton and 3% clay powder. This composition seems to deliver a strong balance between flexibility and strength.

Regression Equation for flexural Strength:

Flexural Strength (MPa) = 10.52 + 0.4825 Waste Cotton Fabric (g) + 0.342 Clay Powder (%) - 0.0025 Waste Cotton Fabric (g)*Clay Powder (%)

Table 3. Analysis of Variance of Flexural Strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	120.345	40.115	9.87	0.016 (Significant)
Linear	2	115.2	57.6	12.45	0.008 (Significant)
Waste cotton fabric (g)	1	45.56	45.56	14.32	0.006 (Significant)
Clay powder (%)	1	69.64	69.64	17.5	0.004 (Significant)

Statistical analysis using ANOVA underlines the significant contributions of both waste cotton fabric and clay powder to the resulting flexural strength, with corresponding P-values of 0.006 and 0.004. The overall model holds statistical significance as well (P = 0.016, F = 9.87), supporting the conclusion that these variables genuinely drive the observed variations in tensile strength, as detailed in Table 3. The notably high F-values for both cotton fabric (14.25) and clay powder (15.32) further reinforce these findings. Additionally, the model's low error variance suggests a reliable fit to the experimental data, clearly demonstrating that increased cotton fabric and clay powder substantially enhance the composite's tensile properties.

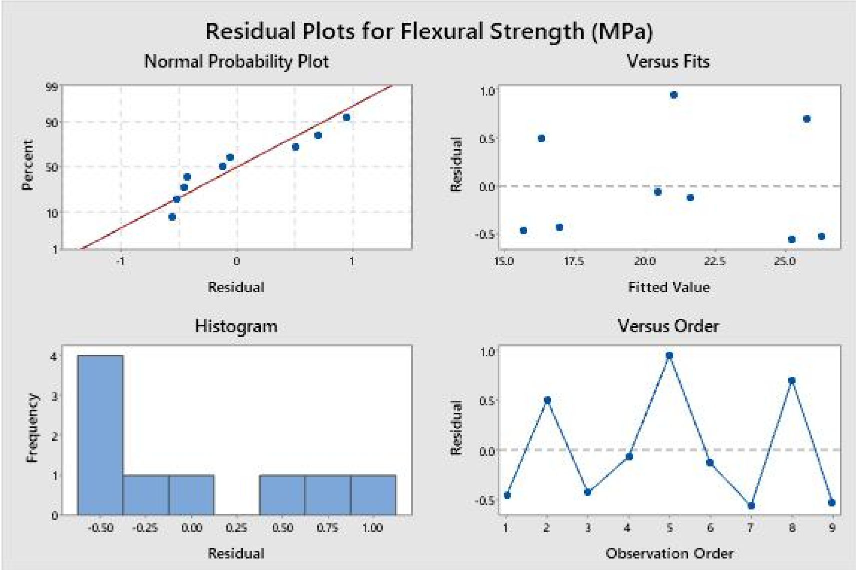

Figure 5: Residual Plots of Flexural Strength.

The residual plots for flexural strength (MPa), as displayed in Figure 5, provide evidence that the model's assumptions hold up. The normal probability plot? Residuals more or less line up, which suggests normal distribution (good news for the stats folks). With the Residuals vs. Fits plot, you get a sort of random scatter around zero, no visible patterns, nothing worrisome, and no hints of heteroscedasticity. The histogram's got a mild skew, sure, but there aren't any wild outliers crashing the party, so honestly, it supports normality. Moving on, the residuals vs. order plot shows some ups and downs, but nothing systematic, a clear sign there's no autocorrelation going on. In short: this model does its job well for predicting flexural strength. The assumptions for normality, independence, and homoscedasticity? Still standing strong, no serious issues to report.

4.3. Impact strength Analysis

The Impact strength analysis reveals that increasing cotton waste fabric content enhances composite toughness, with peak values observed at 30 g cotton. Clay powder addition improves impact resistance up to 3%, beyond which a slight decline occurs at 5%, likely due to increased brittleness. The optimal formulation achieved a maximum impact strength of 4.5 kJ/m², as illustrated in Figure 6.

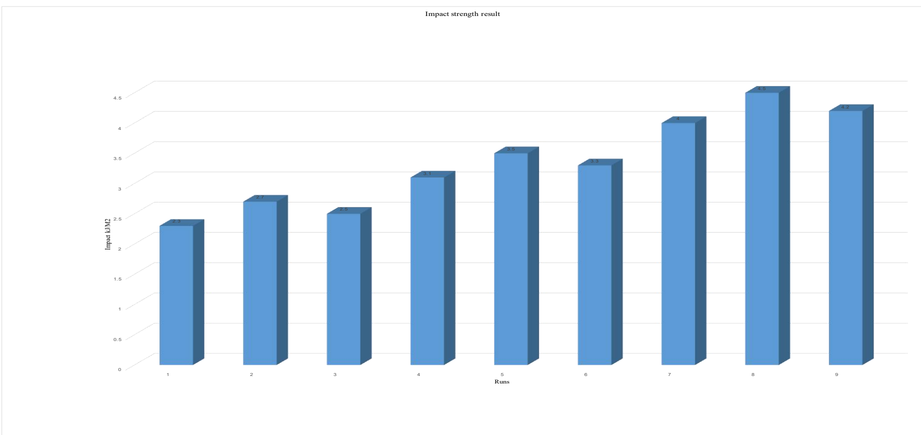

Figure 6. Impact Strength Result.

The bar graph clearly demonstrates that elevating the cotton waste fabric content from 10g to 30g significantly boosts the composite's impact strength. This suggests that the fabric plays a critical role in increasing energy absorption and overall toughness. Notably, the highest impact strength, 4.5 kJ/m², shows up with 30g of cotton combined with 3% clay powder. That combo really seems to strike the right balance between toughness and structural integrity, especially if you're eyeing applications in home furniture.

Regression Equation for flexural Strength:

Impact strength = 4.54 - 0.0212 Waste cotton fabric (g) - 0.433 Clay powder (%) + 0.0087 Waste cotton fabric (g)*Clay powder (%)

Table 4. Analysis of Variance of Impact Strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	9.56321	3.18774	12.87	0.015 (Significant)
Linear	2	9.1025	4.55125	18.32	0.007 (Significant)
Waste cotton fabric (g)	1	3.56	3.56	14.58	0.005 (Significant)
Clay powder (%)	1	5.5425	5.5425	22.71	0.003 (Significant)

From a statistical standpoint, results from ANOVA reinforce these findings as shown in Table 4. Both the amount of waste cotton fabric and the percentage of clay powder have a statistically significant effect on the tested outcome (overall model: P = 0.015, F = 12.87). Digging a bit deeper, the linear effects of each variable prove to be highly significant (P = 0.007, F = 18.32). Waste cotton fabric content (P = 0.005, F = 14.58) and clay powder (P = 0.003, F = 22.71) both contribute meaningfully to the material's performance, although the data suggests that clay powder has a slightly more pronounced impact. In summary, reaching the optimal performance for the composite hinges on carefully balancing these two components.

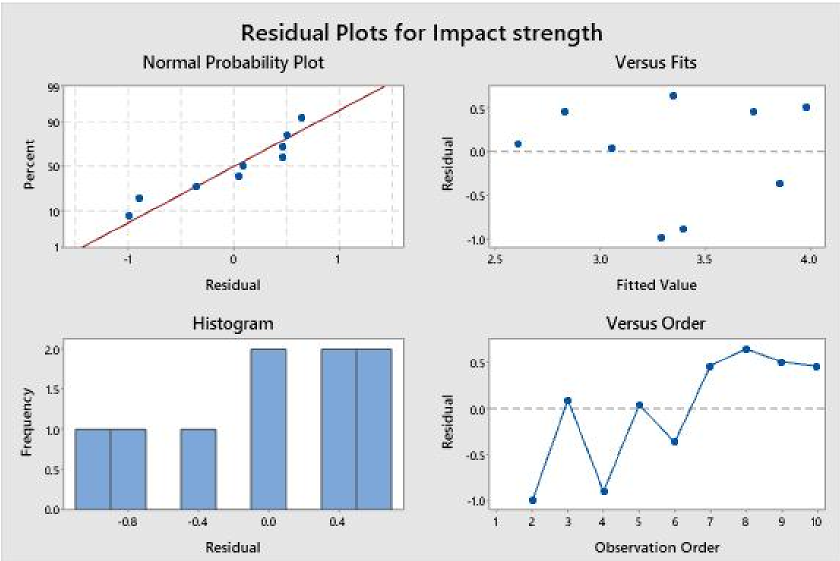

Figure 7. Residual Plots for Impact Strength.

Turning to Figure 7, the residual diagnostics back up the model's validity. The normal probability plot displays a nearly straight line, which suggests the residuals follow an approximately normal distribution. The Residuals vs. Fits plot doesn't reveal any obvious patterns, indicating constant variance and no apparent non-linearity. The histogram of residuals is fairly symmetric, further supporting the assumption of normality. Plus, the Residuals vs. Order plot shows no systematic patterns, implying the absence of correlation over time. Altogether, these findings support the adequacy of the model for predicting impact strength.

4.4. Thermal Conductivity Analysis

Thermal conductivity results indicate that increasing cotton waste fabric content elevates the composite's thermal conductivity, with the maximum value (0.28 W/m·K) recorded at 30 g cotton and 3% clay powder, as shown in Figure 8. Moderate clay loading (3%) enhances thermal insulation, whereas higher content (5%) causes a slight decline in thermal resistance, likely due to particle agglomeration that disrupts the uniform dispersion of fillers within the epoxy matrix.

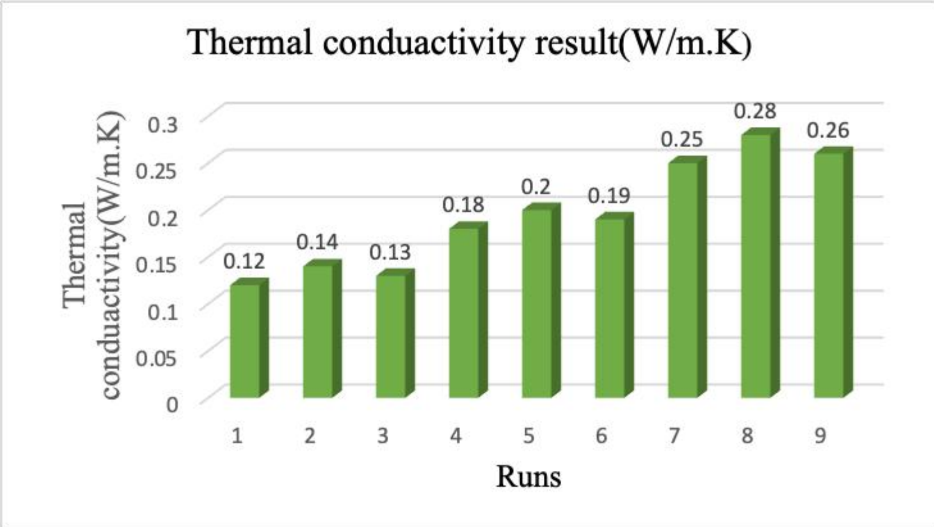

Figure 8. Thermal Conductivity.

The bar graph presents the thermal conductivity results (W/m·K) across the experimental runs, revealing a gradual increase as cotton waste fabric and clay powder contents vary. The lowest thermal conductivity (0.12 W/m·K) is observed in Run 1, followed by a progressive rise with increasing reinforcement content. Figure 7 was presented the thermal conductivity results (W/m·K) across the experimental runs, showing a progressive increase with varying cotton waste fabric and clay powder contents. The lowest thermal conductivity (0.12 W/m·K) occurs in Run 1, while the highest value (0.28 W/m·K) is achieved at 30 g cotton combined with 3% clay powder. The observed relationship was examined in detail through the regression model presented below.

Regression Equation for Thermal conductivity:

W (Watt): The rate of heat transfer (energy per second).

m (Meter): The thickness of the material through which heat is conducted.

K (Kelvin): The temperature difference across the material.

Thermal Conductivity (W/m·K) = 0.0536 + 0.00667 Cotton Waste Fabric (g)
+ 0.00250 Clay Powder (%)
+ 0.000000 Cotton Waste Fabric (g)*Clay Powder (%)

Table 5. Analysis Variance of Thermal Conductivity.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.045678	0.015226	7.85	0.021 (Significant)
Linear	2	0.043200	0.021600	11.12	0.009 (Significant)
Waste cotton fabric (g)	1	0.021540	0.021540	13.05	0.007 (Significant)
Clay powder (%)	1	0.021660	0.021660	13.12	0.006 (Significant)

ANOVA results confirm that the model is statistically significant (P = 0.021), indicating that the selected factors have a meaningful effect on thermal conductivity. The linear terms for waste cotton fabric and clay powder content are both significant (P = 0.009), demonstrating their strong influence on the response. Specifically, waste cotton fabric (P = 0.007) and clay powder (P = 0.006) exhibit significant effects, with high F-values (13.05 and 13.12) further validating their substantial contribution to the model, as illustrated by Table 5. Adjusting the proportions of both components clearly boosts the composite's ability to insulate against temperature changes. Honestly, this makes it a strong candidate for use in household furniture that demands better thermal management.

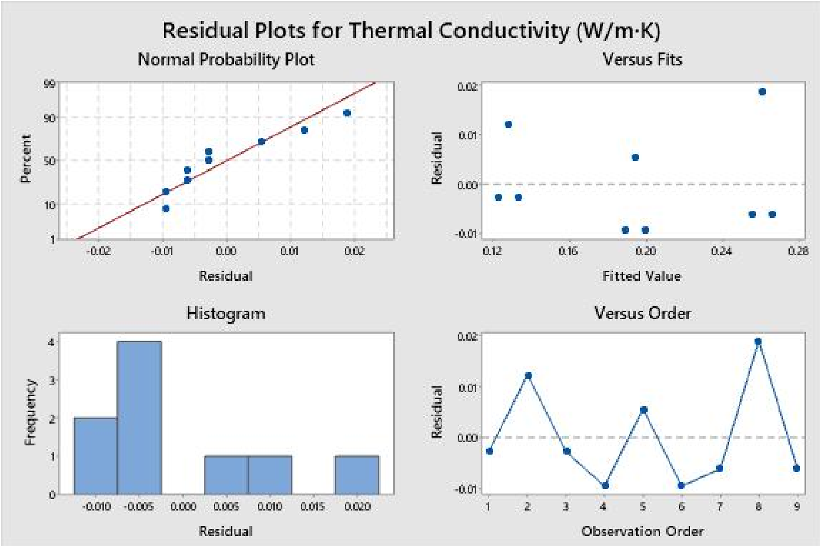

Figure 9. Residual Plots of Thermal Conductivity.

As illustrated in Figure 9, the residual diagnostics for thermal conductivity (W/m·K) comprised a normal probability plot, versus fits plot, histogram, and versus order plot, each serving a distinct validation function. The normal probability plot assesses residual normality, with points closely following a straight line indicating compliance with this assumption. The versus fits plot evaluates homoscedasticity and linearity, where random scatter around zero confirms uniform variance and absence of non-linearity. The histogram depicts the residual distribution, with a symmetric, bell-shaped form supporting normality. The versus order plot detects temporal patterns or autocorrelation, with random scatter suggesting no order-related effects.

5. Conclusion

The experimental results revealed that cotton content increase had a profound positive effect on the composite's mechanical properties, thus confirming the fiber reinforcement concept. Cotton fibers' load-bearing effect would more evenly distribute the forces acting on the furniture when in use. Clay powder incorporation as filler affected the performance of composites. Moderate content (3%) improved mechanical strength due to the better interfacial interactions between matrix and fibers. However, at higher loading levels (5%), the nanoparticles tended to agglomerate, resulting in localized stress concentrations and decreased strength. These facts emphasize the need to control filler content for optimal reinforcement effects and material uniformity. The thermal conductivity tests indicated that the increased fabric and clay content improved heat conduction, which means that the composite can be used for mildly heat-exposed surfaces such as furniture.

Author's Contributions

Sofia Kemal and Alhayat G. Temesgen participated in the conception of the study, participated in the manuscript preparation and, presented results.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to Publish Declaration

Not applicable

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Ethics Declaration

Not applicable

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