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ORIGINAL CONTRIBUTION

Study on Low-Velocity Impact Performance of Chemical Treated Flax Fibre-Reinforced Aluminium 6082 Laminates

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Abstract The experimental studies of drop weight and Izod impact test of FFAL (flax fibre aluminium laminate) are presented in the research. The materials taken for the study are plain woven flax and aluminium lamina with epoxy resin as an adhesive material. Alkaline with diluted epoxy chemical treatment is added to flax, and aluminium is treated with NaOH to strengthen the binding between the fibres and metal. The FFAL was prepared by hand layup method followed by compression moulding technique. The low-velocity and Izod impact tests were conducted for treated and untreated samples. The outcomes exhibited that the increase in the impact strength of 40% and energy absorption capacity of low-velocity impact strength also improved for the treated sample. The experimental damage of low-velocity and Izod impact test results are also examined.

Keywords FFAL · Chemical treatment · Drop weight test · Izode Impact Test

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Introduction

The stacked layers of thin metal sheets and fibres (natural/synthetic) are a new type of lightweight material widely used in aerospace and defence applications because of good mechanical properties like high strength-to-weight ratio, good corrosion resistance, high stiffness, good impact resistance and wear resistance [1–3]. The investigation of ecologically friendly materials has been spurred by rising environmental consciousness, heightened community interest, and more stringent environmental laws. Natural fibres have become a strong alternative because of their advantages over synthetic fibres [4–6]. Because of the numerous benefits provided by natural fibres, there has been a significant increase in demand for fibre metal laminate in recent years [7–10]. These benefits include lightweight composition, affordability, and minimal impact on machinery during processing, favourable mechanical properties such as tensile and flexural modulus, improved surface finish, and abundant availability as renewable resources, processing adaptability,

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biodegradability, and concurrent reduction in health risks [11–15]. However, it is important to remember that natural fibres may have some disadvantages. Their composition of cellulose, hemicelluloses, lignin, pectin, and waxy materials allows them to absorb moisture from the surrounding air, which causes the link between the polymer and fibre to become weak [16–20]. Furthermore, the various chemical structures of polymer matrices and natural fibres make it difficult to achieve good coupling at the interface, which results in ineffective stress transfer inside the composites [1, 7, 18, 21, 22]. Certain procedures are used to alter natural fibres in order to address these problems. Reagent functional groups are commonly used to improve composite materials. These groups have the ability to interact with fibre structures, altering their composition [23–27]. When fibres improve the adhesive characteristics between themselves and the matrix, the overall performance of composite materials improves, effectively minimising moisture absorption [28–30].

Extensive research has been dedicated to examining the behaviour of materials like carbon-reinforced aluminium, aramid-aluminium laminate, and glass fibre-aluminium laminates through low-velocity impact experiments, often comparing them with metals such as titanium and magnesium [31–35], and these material are promising in the field of automotive and defence sector; specifically, it can be used as car front hood, back panel, tail gate, bumper, fender and body armour, etc. These experiments have provided valuable insights into how fibre metal laminate (FML) responds to impact forces. One prominent challenge identified in FML during low-velocity impacts is laminate delamination. Parameters such as interfacial adhesion, energy absorption, and deflection stiffness are crucial factors associated with FML delamination [36–41]. Notably, surface treatment applied to both the fibre and metal layers serves to enhance inter-laminar strength, thereby improving the overall mechanical characteristics of the laminate.

Aghamohammadi et al. [15, 26, 27] investigated various surface treatment and their effects on the flexural properties of aluminium metal fibre laminate. The treatment effect on fibre metal laminates (FMLs) helps to improve their impact characteristics. Despite this, there are few reports on the use of flax fibre in FMLs. Mujahid Khan et al. [16, 30] investigated the mechanical characteristics of epoxy composites reinforced with banana fibres after alkali treatment. The purpose of alkaline treatment or retting is to break down the pectins and other components that bind the fibres together in the flax, and when it is treated with flax fibre, following changes happen fibre softening: the treatment can result in softer and more pliable fibres, making them more suitable binding with other fibres or metals. Improved fibre quality: alkaline treatment can lead to an improvement in the quality of the flax fibres by removing impurities and unwanted substances from the raw material. After fibre treatment with a 4.5% NaOH solution, the results demonstrated a general increase in mechanical properties, notably tensile and compressive strengths. When compared to the untreated sample, the treated samples showed significant improvements, with a 24.2% increase in tensile strength and a 34.8% rise in compressive strength. This treatment elevates the material to the status of structural alloy with enhanced strength properties. The greater strength of aluminium alloy 6082 over 6061 has contributed to its growing popularity in a variety of applications. This alloy is preferred because of the considerable manganese addition, which allows for better control over the grain structure and higher material strength. R. Eslami Farsani et al. [17, 31] studied the influence of adding micro glass powder into basalt fibre-reinforced epoxy composites. Unlike epoxy composites reinforced merely with basalt fibre, the inclusion of tiny glass powder increases energy absorption, particularly at high temperatures.

Natural fibre-laminated composites are prone to delamination due to their inherent low inter-laminar strength. The polymeric matrix within the composite is critical in promoting energy transmission among its components to improve impact energy absorption. Delamination between layers may occur with minimal apparent surface damage in low-velocity impact scenarios, although real piercing is uncommon [42–47]. Contaminated reinforcing fibres, insufficient fibre wetting, mechanical stress during machining, and insufficient reinforcement in the thickness direction are all variables that might lead to pre-existing delamination inside a composite. These flaws have the ability to drastically reduce the energy absorption capacity of the composite [48–52].

Over time, research on metal laminate made of natural fibres, such as flax fibres, has made steady progress. Surprisingly, in spite of these advancements, there is a glaring deficiency in comprehensive review papers targeted specifically at flax composites. In order to gain a foundational understanding for future research in the field of natural fibre metal laminate, the study thoroughly examines flax fibres and aluminium lamina, their surface treatments, the production of treated and untreated NFML, mechanical testing, and microstructural analysis.

Materials and Methods

Materials

Vruksha composites, Guntur, A.P., offered a unidirectional flax fibre with the following properties: 1.31 g/cm^3, 0.65 mm thickness, 365 MPa tensile strength, 35 GPa tensile modulus, 294 MPa maximum flexural strength, and 50% fibre fraction by volume. For this project, PMC Corporation in Bangalore, Karnataka, offered aluminium 6082 with a density of 2.71 g/cm^3, a Young's modulus of 70 GPa, an ultimate tensile strength ranging from 141 to 335 MPa, a yield strength of 270 MPa, and a thickness of 1 mm. The hardener and epoxy resin LY556 were also purchased from CS Marketing in Bangalore, Karnataka. At 250 °C, LY556 has a viscosity varying from 10,000 to 12,000 MPa and a density ranging from 1.15 to 1.2 g/cm^3. It also has a flash point of 1950 °C. The optimum ratio of epoxy to hardener during mixing was found to be 10:1. About 150 g of epoxy was taken along with 15 g of hardener.

Alkaline Treatment for Aluminium 6082

The aluminium alloy sheets underwent a treatment process wherein they were immersed in an alkaline solution bath at a temperature of 65 °C for duration of 1 min. Subsequently, the sheets were thoroughly cleaned and dried using clean water. This process is likely employed for surface treatment or preparation, and the specific conditions mentioned suggest a carefully controlled procedure for enhancing certain properties or characteristics of the aluminium alloy sheets.

This solution contains 35 g/L sodium hydroxide and 35 g/L sodium carbonate; this allows for better roughness on the surface of the aluminium, and also the chemicals allow for better bonding with the treated flax fibres. Figure 1a–d shows the treatment process of Aluminium 6082.

Chemical Treatment for Flax Fibre

The flax fibres by themselves have a rough nature. The treatment of flax fibres helps in increasing the bonding between the matrix and the flax fibres and also helps increase other properties due to the removal of pectins [20].

Several procedures were required in the manufacture of the flax fibre unidirectional (UD) mats. The mats were first immersed in a 1% concentration sodium hydroxide (NaOH) solution at room temperature for 20 min. Following the immersion, the fibres were thoroughly cleaned in cold water and then in acidified water (made by adding 20 drops of 0.1 M hydrochloric acid to 1 L of water) to remove excess NaOH. After that, a final rinse with cold water was

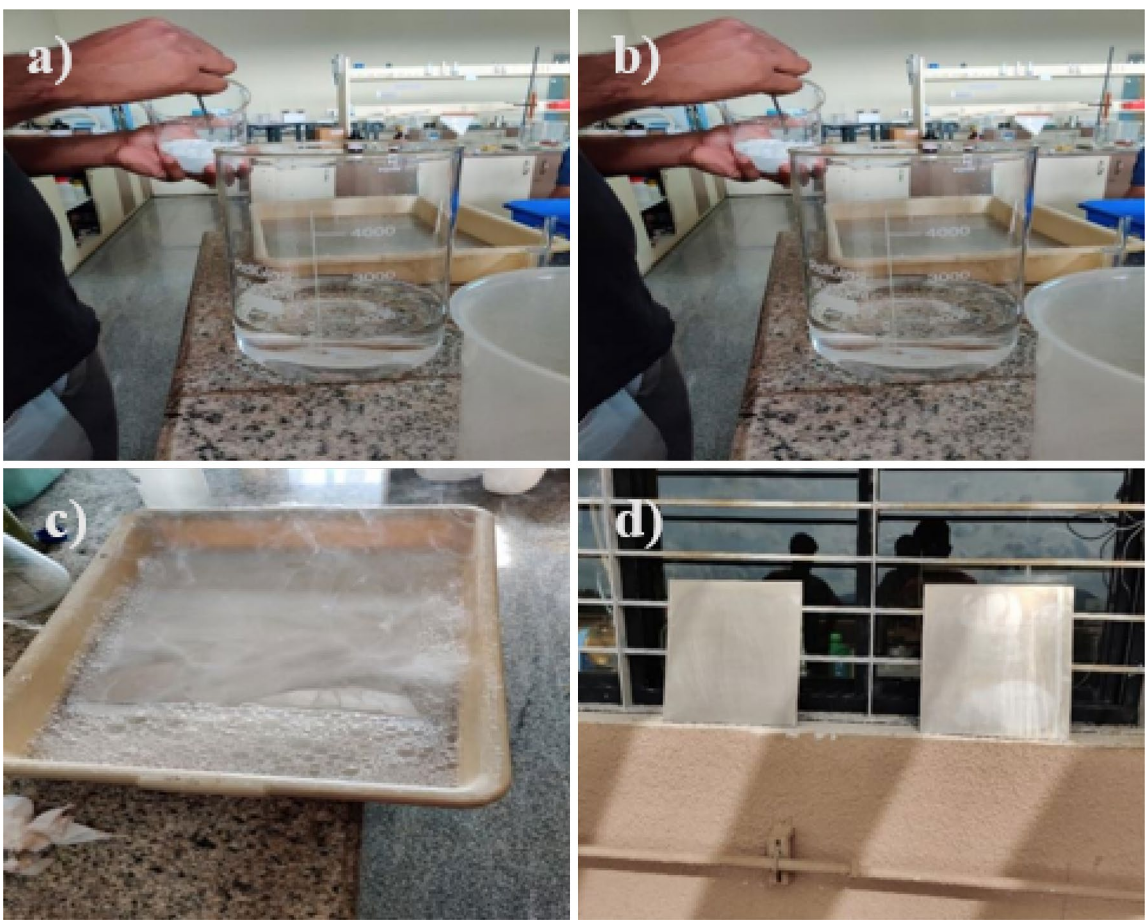


Fig. 1 **a** 30 g/L solution of NaOH is created by adding 60 g NaOH in 2L of distilled water. **b** 30 g/L solution of Na_2CO_3 is created by adding 60 g Na_2CO_3 in 2L of distilled water. **c** The aluminium sheets are dipped inside the solution (heated to 60 °C for 1 min. **d** The aluminium sheets are dried in air

conducted. The cleaned fibres were then dried for eight hours in an oven set at 80 °C. The fibres were then submerged in acetone-dissolved epoxy, precisely a 3% solution of epoxy LY556. This epoxy application lasted two hours at ambient temperature. The full methods involved in the alkaline and dilute epoxy treatment of flax fibre are depicted in Fig. 2a–i. This extensive procedure is most likely used to improve the compatibility and bonding properties of the flax fibres with the epoxy matrix in the composite material.

Specimen Preparation

The fabrication method used was the hand-layup method followed by compression moulding technique. One of the most basic and affordable methods for fabricating NFML is through the hand-layup technique. This method involves layering the materials in a calculated ratio by volume and then fabricating those layers by hand. The manufacturing procedure in this study entails generating layers consisting of dual layers of flax fibres sandwiched between two layers of aluminium. The epoxy is made by combining it with the hardener in a 10:1 ratio. Following that, the epoxy mixture is poured over each layer and uniformly dispersed, as shown in Figures 3(a–b). Finally, the layers are layered on top of one another. This assembly method implies the formation of a composite structure in which flax fibres, aluminium layers, and an epoxy matrix are mixed to produce a cohesive and integrated material for further study or application [53–57].

The drawbacks of the hand-layup process (Fig. 3a, b) are that the composite will not have enough pressure or heat to bond evenly throughout the material during the process and that the epoxy may not spread as evenly when spread by hand. This is overcome by using compression moulding (Fig. 3c) right after this process. The purpose of

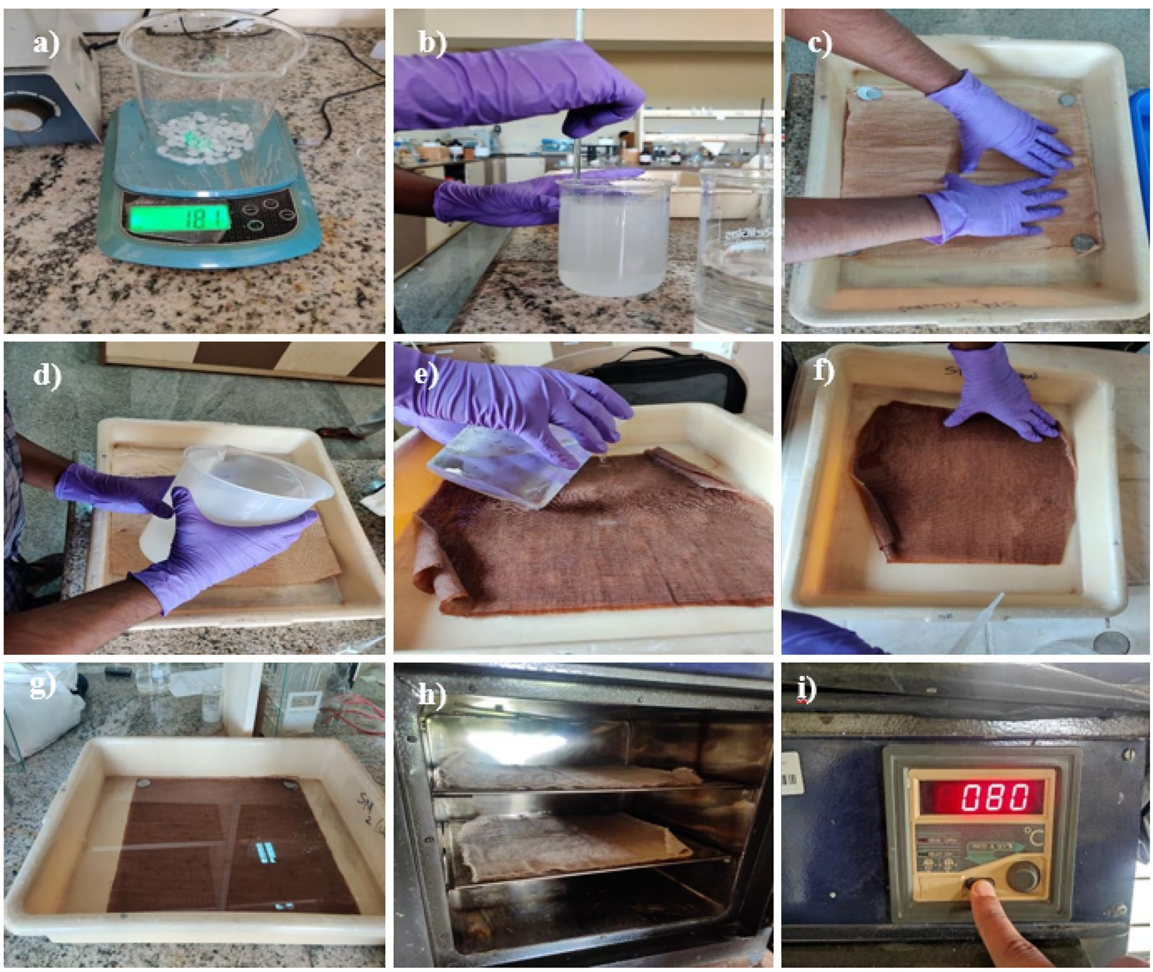


Fig. 2 **a** Weighing of NaOH crystals upto 20 gms. **b** Mixing of NaOH with 2000 ml distilled water for 1% NaOH solution. **c** Setting up flax fibres for the pouring process. **d** The 1% NaOH solution is poured onto the flax fibres and left for 20 min. **e** 1000 ml of distilled water is poured onto the fibre. **f** Twenty-five drops of 0.1 M HCl are dropped into the water and mixed to get rid of excess NaOH in the fibres. **g** 30 g of epoxy LY556 in 1L acetone with a few drops of hardener. **h** The treated fibre is kept in an oven. **i** The temperature is set to 80 °C and it is left for 8 h

Fig. 3 **a**, **b** Hand-layup process of FFAL. **c** The compression moulding apparatus. **d** The compression and heater plates inside the apparatus. **e** The material is kept inside the apparatus and a pressure of 30 bar is applied. **f** The heaters are heated to 70 °C and then left for 4 h

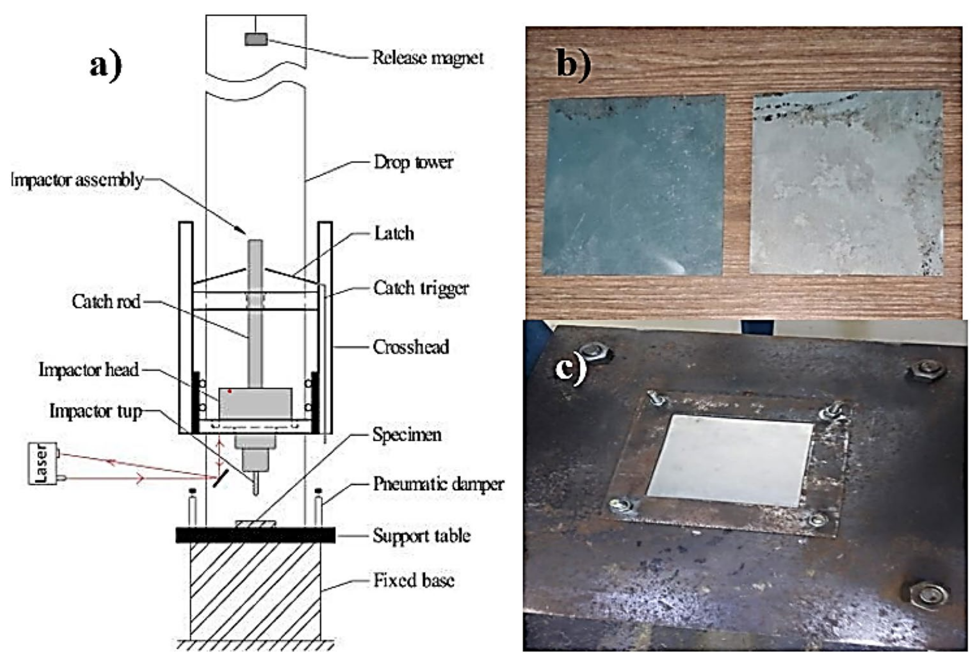
this process is to evenly spread the epoxy among the layers and to provide pressure and heat as shown in Fig. 3d–e. This allows the epoxy to harden and cause the bonds between the metal and fibre to strengthen while adhering the two together, therefore acting as a sort of curing process Fig. 3f and help in increasing mechanical properties.

Impact Tests

Impact Drop Weight Test

The INSTON 9520HV testing device was used for the drop weight tests. Figure 4a depicts a schematic representation of the arrangement. The parameters of the drop weight test

Fig. 4 **a** Schematic diagram of drop weight testing machine. **b** Sample size treated and untreated. **c** Specimen clamped for testing



are specimen geometry, notch configuration, drop weight, drop height, impact velocity. The drop hammer utilised in the testing was outfitted with an acceleration sensor that recorded the acceleration history during the impact. The specimens utilised in the testing were 100 mm square with a thickness of 3 mm, as shown in Fig. 4b. This experimental setup and specimen size suggest a controlled way for evaluating the impact resistance and behaviour of the materials or structures under consideration. The use of an acceleration transducer enables extensive monitoring and analysis of the acceleration dynamics during drop weight testing.

Drop weight impact testing was performed on both treated and untreated flax fibre-reinforced aluminium (FBAL) specimens. Figure 4c depicts the experimental setup, which included clamping the specimens between two square steel plates with a central square aperture. The apertures in the steel plates were 70 mm in diameter. The 6.2 kilogramme impacting projectile utilised had a hemispherical diameter of 10 mm. As seen in Table 1, the drop weight heights were consistently fixed at 1 m. This arrangement and the settings indicated imply a controlled testing environment for evaluating and comparing the impact resistance of treated and untreated FBAL specimens under consistent conditions [58–62].

Izod Impact Test

The Izod impact test evaluates a material's impact resistance by measuring the energy it can take before breaking under a single applied force. A material specimen is placed in a pendulum-like contraption, which is subsequently hit by a weighted pendulum. The pendulum swings downward upon contact, and the following rise in height is measured to calculate the amount of energy absorbed by the specimen. The Izod impact test findings are stated in terms of the energy absorbed by the specimen prior to breaking. This impact energy value is critical for determining the material's resistance to impact forces. Figure 5 shows a schematic illustration of the Izod impact test, exhibiting the fundamental set-up and mechanics of the test.

Table 1 The impact test parameters

Test parameters	
Displacement	17 mm
Mass	6.3 kg
Drop height	1 m
Velocity	4.5 m/s
Acceleration	1620.45 m/s^2
Energy	60 J

Results and Discussions

Drop Weight Test Results

Drop weight impact test, the acceleration vs. time curve illustrates the dynamic response of a material to sudden impact forces. As the test begins, the curve typically starts with zero acceleration as the weight is at rest, and it accelerates downward rapidly once released, primarily due to gravity. Upon impact with the material specimen, the acceleration drops abruptly to zero, indicating the moment of impact. Subsequently, the acceleration may exhibit fluctuations, which are often associated with the material's ability to absorb and release energy through elastic deformation.

The force vs. time curve in a drop weight impact test illustrates how a material responds to sudden impact forces. It begins at zero force, accelerates rapidly upon impact, reaches a peak force at the moment of impact, and then may exhibit fluctuations or a gradual decline as the material undergoes deformation. The curve concludes with a sharp drop to zero force at the point of catastrophic failure, indicating the material's ultimate strength and ability to withstand dynamic loading conditions, making it crucial for evaluating impact resistance and material suitability in various applications.

The energy vs. time curve in a drop weight impact test shows the transfer and absorption of kinetic energy during

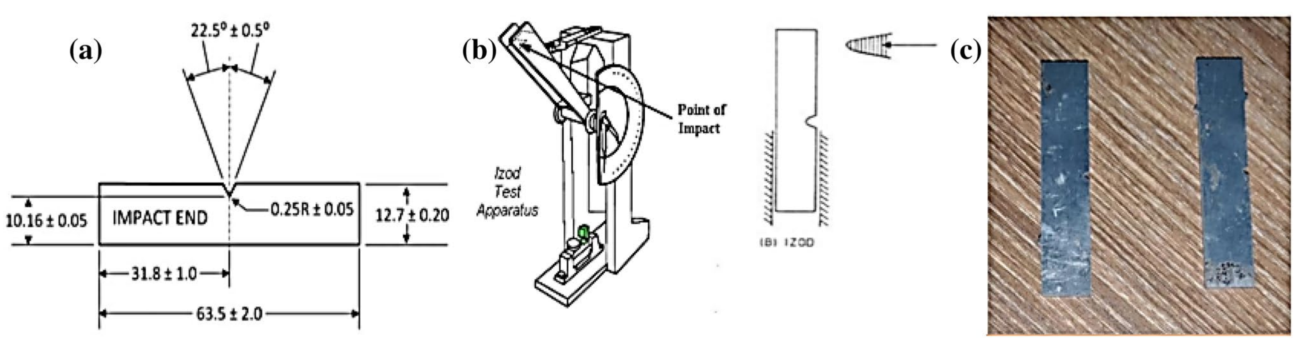


Fig. 5 **a** Sample dimensions as per ASTM D256 sample size, **b** schematic diagram of Izod impact tester and **c** sample for testing

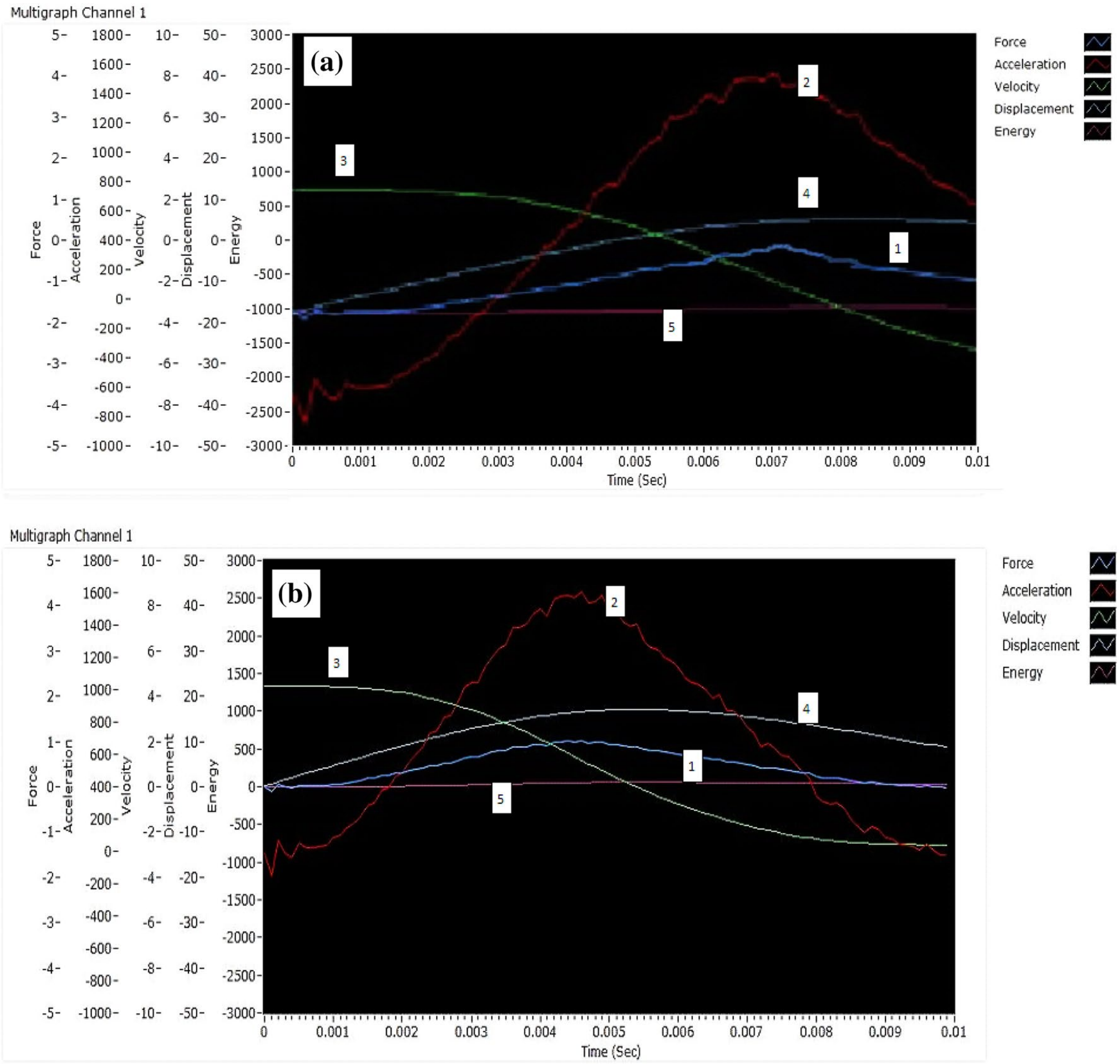
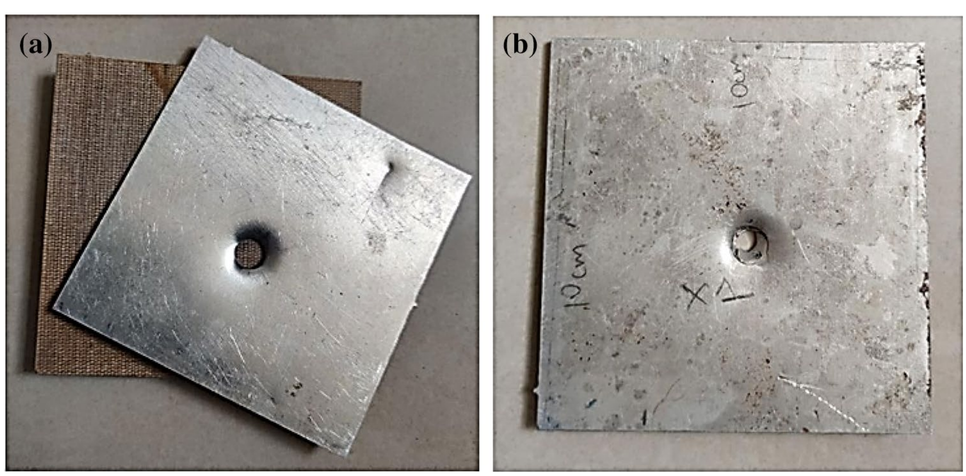


Fig. 6 Drop weight results for **a** untreated sample and **b** treated sample

Fig. 7 Drop weight of **a** untreated and **b** treated samples of FBAL



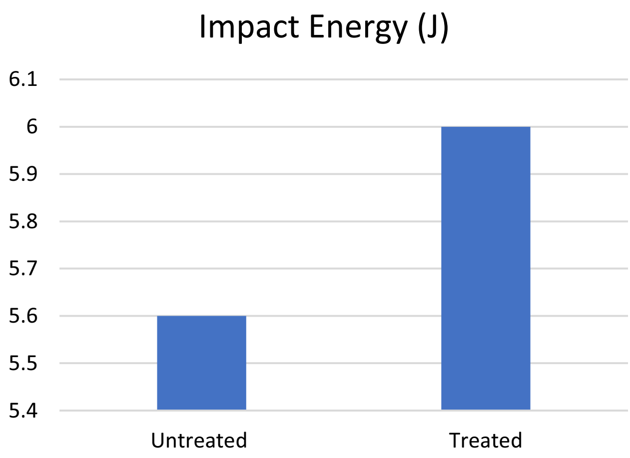


Fig. 8 Impact energy of treated and untreated FBAL

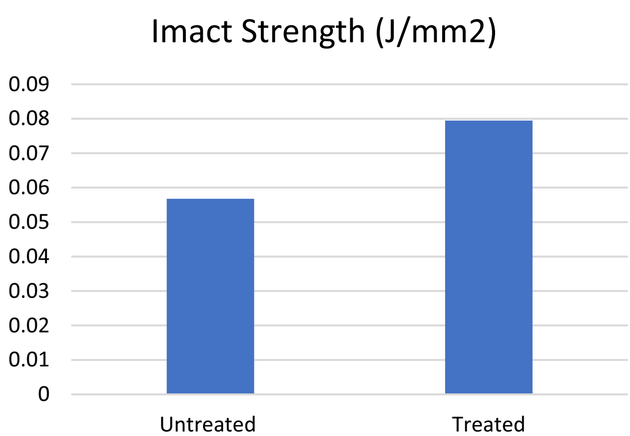


Fig. 9 Impact strength of treated and untreated FBAL

an impact event. Starting at zero, it rapidly increases as the weight accelerates due to gravity. Upon impact with the material, there is a sudden spike in energy, representing the instant energy transfer from the weight. The curve may then fluctuate or gradually rise as the material absorbs and releases energy through deformation. It concludes with a peak, signifying the maximum energy absorbed before material failure. This curve provides insights into the material's energy dissipation and its ability to withstand dynamic loading conditions, aiding the assessment of its impact resistance and suitability for applications.

The displacement vs. time curve in a drop weight impact test illustrates the motion and deformation of a material under sudden impact. Starting at zero displacement, it rapidly increases upon impact, showing an initial jump at the moment of contact. Subsequently, the curve may exhibit fluctuations or a gradual rise as the material undergoes elastic or plastic deformation. It concludes with a sharp spike at the point of catastrophic failure, representing the maximum deformation the material can endure. This curve offers critical insights into the material's deformation behaviour and damage characteristics under dynamic loading conditions, aiding in the assessment of its impact resistance and structural integrity for various applications.

The velocity vs. time curve in a drop weight impact test tracks the motion of a material under sudden impact. It begins at zero velocity and rapidly increases as the weight accelerates due to gravity. Upon impact with the material specimen, the velocity drops abruptly to zero, signifying the instant of contact. The curve may then exhibit fluctuations or a gradual decline as the material undergoes elastic or plastic deformation, depending on its response. Ultimately, it concludes with a sharp spike at the point of catastrophic failure, representing the maximum deformation the material can sustain. This curve provides crucial insights into the material's dynamic behaviour, energy absorption, and impact resistance, aiding in its suitability assessment for various applications [63–67].

The forces, acceleration, displacement, energy, and velocity lines of the treated and untreated samples are clearly different, as the graph in Fig. 6 shows. The treated sample's results line deviates slightly from the other data, suggesting that it has a higher energy-absorbing capacity than the untreated sample [68–71].

This demonstrates that the sample that has been treated can absorb more energy, offering greater protection against energy impacts (Figs. 7, 8, 9, 10).

Izod Impact Test Results

The average impact strength of the untreated specimen was 0.0618 J/mm^2, while the treated specimen had higher impact

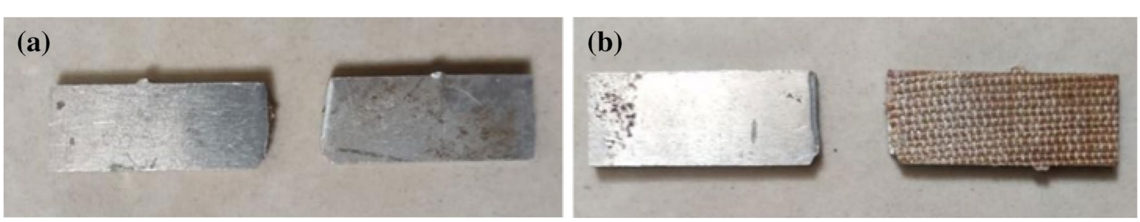


Fig. 10 Tested samples after impact test, **a** treated and **b** untreated

strength of 0.0801 J/mm^2. As a result, the treated specimen had an impact strength that was almost 40% more than the untreated one. This increase in impact strength indicates that the treatment had a beneficial effect on the specimen's capacity to absorb energy before fracture under impact pressures.

The treated sample absorbs 12% more impact energy than the untreated sample. The improved findings are mostly due to FFAL's ductility, which absorbs the shock load for the treated sample.

Conclusion

The effect of surface treatment on low-velocity impact performance and Izod impact characteristics was investigated in the context of aluminium 6082 and flax fibre. Aluminium 6082 was treated with NaOH in this study, whereas flax fibre was treated with alkaline. The test findings demonstrated that the layer-by-layer fabrication of the material increased the surface energy, formed covalent connections, and created a porous structure on the surface of flax fibre and aluminium 6082, improving the inter-laminar characteristics of FFAL. The bonding ability of aluminium is improved by the NaOH treatment for aluminium and the alkali treatment for flax. When compared to the untreated sample, the treated specimen's impact strength increased by 40%, according to the results. The treated sample exhibited a remarkable enhancement in adhesion properties and absorbed 12% more impact energy than the untreated sample. By comparing force line curves between the treated and untreated samples, the low-velocity impact strength of the treated sample suggests a greater potential for energy absorption. This demonstrates that the sample that has been treated can absorb more energy, offering greater protection against energy impacts.

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Data Availability Not applicable.

Declarations

Conflict of interest The writers claim that there are no any conflicts of interest.

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