International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 07 July 2025, pp: 184-191 www.ijaem.net ISSN: 2395-5252

Development of Armour Plates Using Kevlar Woven Fibre/Epoxy Resin Composites

Alimi Nofisat, Agboola Oladipo
Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna, Nigeria

Date of Submission: 01-07-2025 Date of Acceptance: 10-07-2025

ABSTRACT

This research investigated the development of armor plates utilizing Kevlar woven fiber as reinforcement, epoxy resin as the binder, and 2,4,6-Triamino-1,3,5 triazine as a fire retardant additive. Ten samples (AP1- AP10) were fabricated using hand laying and compression molding techniques. Mechanical properties tests including: tensile strength, flexural strength, hardness, impact strength and thermogravimetric analysis were carried out on the fabricated samples. The results revealed that sample AP5 has the best properties with highest tensile strength of 71.25 MPa and tensile modulus of 523.897 MPa, indicating superior structural integrity; greatest flexural strength (141.20 MPa) and flexural modulus (5.097 GPa); adequate impact resistance with an impact strength of 0.1168 J/mm and hardness value of 64.67Hv. Thermogravimetric analysis indicated critical thermal degradation properties, revealing significant differences among samples in terms of thermal stability. The armor plate was developed using sample AP5. The ballistic performance tests confirmed that the developed composite plates from AP5 effectively resist penetration from the AK-47's 7.62mm x 39mm rounds at distances of 100m and 75m. However, performance decreases at closer ranges (50m and 25m), suggesting a critical threshold for effective ballistic protection. The findings emphasize the importance of optimizing composite design to mitigate vulnerability to laminate failure under varying impact conditions. Overall, this study contributes to advancements in ballistic protection materials, potentially enhancing safety in defense applications.

Key words: Amor plate, Kevlar woven fibre, epoxy resin, 2,4,6-Triamino-1,3,5 triazine, fire retardant

I. INTRODUCTION

Threats in the military combat operations have made defense industry in conjunction with the scientific community to continue to show great interest in the development of protective armor systems. One of the major threats is the impact of projectiles at medium and high-speed during combat operation. Body armors play a considerable role in reducing injuries that might lead to disabilities and deaths in war fighting, counter-terrorism operations, and public security missions. The Global Terrorism Index (GTI) shows that wars and terrorist attacks have increased in 30 years. During 2011 and 2014, armed assaults and explosions were the main causes of death up by 400% compared to the previous decades [1]. Therefore, the need for high level ballistic protection against bullets and shrapnel for military and paramilitary officers has been a significant challenge for indigenous engineers [2]. The efficiency of these protective systems depends strongly on their ability to resists impulsive forces and absorb energy. Hence, it has become critical to develop new methods of improving the impact resistance of materials used for protective armor applications. Armor systems having high-performance and lightweight have always been the aim in the development of modern military protective wares and is also one of the most significant military research issues today [3]. After World War II, high-performance composites with low density have been gaining preference in making armour vests [4]. Currently, synthetic laminates based on aramid fiber [Kevlar/Twaron]; ultra-high-molecular-weight polyethylene [Dyneema/Spectra Shield], and PBO fiber [Zylon] are commonly used as backing in bulletproof vests [5,6,7]. In a recent review, Benzait and Trabzon stated that the emergence of new materials with outstanding stiffness and strength, as well as light density and high energy absorption, makes them a future choice for ballistic armour materials [8]. This research therefore, focused on developing a high performance and lightweight armour plate to reduce gear weight been carried by soldiers with a view to improving their efficiency during combat operations using locally sourced materials.

II. EXPERIMENTAL

2.1 MATERIALS/EQUIPMENT

The following materials and equipment were used to carry out the study:

Kevlar Fibre, Epoxy Resin, Hexamethylene Tetramine, 2,4,6-Triamino-1,3,5-triazine, Plastic mixing bowl, Glass rod, Metal mould, Hot Air Oven, Compression Moulding Machine, Universal Testing Machine, Resil Impact Tester, Universal Material Testing Machine, Digital Weighing Balance, Microhardness Tester, Thermographic Analyzer, Scanning Electron Microscopy.

2.2 PROCEDURE

The Kevlar was cut into an existing metallic mould size of 140 mm x 120 mm length and width respectively. The Kevlar was dried in a hot air oven at a temperature of 70°C for 60 minutes to remove moisture according to Vikrant Kumar et al [9]. Thereafter, the dried Kevlar fibre was carefully stored in an air tight polythene bag. The Epoxy resin was formulated as shown in table 1. The armor plate composite samples were prepared by hand-laying and compression moulding methods which involved mixing of epoxy and hardener in the ratio of 2:1 respectively in a mixing bowl for 2 minutes to achieve homogenous mixture of epoxy resin, 2,4,6-Triamino-1,3,5-triazine additive was added accordingly and further mixed for 3 minutes until a uniform additive distribution was obtained. Few epoxy resin mixture was poured on the mould cavity measuring 140 mm x 120 mm x 3.2 mm which has already been prepared with aluminum foil and paraffin wax for easy removal of the composite after formation and the Kevlar fibre mat was carefully laid on the resin in the mould with slight application of pressures using paint brush. The top surface of the Kevlar fibre mat in the mould was filled with more epoxy resin and covered with a metallic plate. The samples were cured on hot hydraulic compression moulding machine at 130°C temperature and pressure of 2.5 MPa for 5 minutes for curing. At the end of the curing time, the mould was opened and the sample was carefully removed, placed on a flat surface and further allowed to stand for 24 hours for completely curing at room temperature. The produced samples were labelled as shown in figure 1 according to Vikrant Kumar et al [9].

Table 1: Formulation of Kevlar Woven Fibre/Epoxy Resin Armor Plate Composites

Sample	Epoxy Resin	Kevlar	Additive
AP1	90	`5	5
AP2	85	10	5
AP3	80	15	5
AP4	75	20	5
AP5	70	25	5
AP6	65	30	5
AP7	60	35	5
AP8	55	40	5
AP9	50	45	5
AP10	45	50	5

Figure 1: Produced armour plates for mechanical, physical, morphological and thermal analyses

2.3 MECHANICAL TEST

Tensile strength was carried out in accordance with ASTM D-638. Dumbbell shaped samples were subjected to a tensile force and tensile strength, tensile modulus percentage elongation at Peak for each sample were calculated and recorded automatically by the machine.

Impact test was carried out according to the standard specified by ASTM D-156. The specimen was cut to dimensions 64 mm x 12.7 mm x 3.2 mm and 45° notched was inserted at the middle of the test specimens from all the produced composite samples.

Hardness test was carried out in accordance with ASTM D2240 on a Micro Vicker Harness Tester. The test was carried out at three different points on each sample and average hardness was calculated.

Flexural strength test was carried out in accordance with ASTM D-790 using universal testing machine. The specimen measuring 140 mm x 15 mm x 5 mm was placed on a support span horizontally at 80 mm gauge length and a steady load was applied to the center by the loading nose producing three-point bending until the sample specimen failed. The maximum load (N) and the corresponding deflection (mm) were recorded accordingly as the sample specimen failed.

Microscopic examination of the selected blend samples was done in accordance with ASTM E986 using Scanning Electron Microscope. A piece of cross section of the sample weighing 0.5g was cut and mounted on the sample holder. The sample holder was carefully inserted beneath the magnification screen of the machine and the chamber was closed. The microscopic features of the sample were viewed and a particular area of the microscopic feature was magnified under electron microscopy at different magnification until clear electron features of the samples were viewed and recorded accordingly.

Thermographic Analysis was performed using a Q5000 IR TA Instruments under nitrogen and air conditions.Samples were measured in an alumina crucible with a mass of about 11-13 mg. Composites in an open pan was tested at temperature ranging from 25 to 800°C with a heating rate of 10°C/min in accordance with ASTM E1131.

III. RESULTS

The results of the various tests are presented in the tables and figure below:

Table 2: Results of mechanical tests.

S/N	Sample	Tensile Strength (MPa	Tensile Modulus (MPa)	Flexural Strength (MPa)	Impact Strength (J/mm)	Hardness (Hv)
1.	AP1	63.50	477.444	123.83	0.7168	66.70
2.	AP2	62.50	443.262	131.02	0.7152	67.63
3.	AP3	58.75	379.032	139.45	0.9238	70.03
4.	AP4	70.00	500.000	123.31	0.9218	71.57
5.	AP5	71.25	523.897	141.20	0.9364	64.67
6.	AP6	61.25	428.322	115.62	0.9094	68.90
7.	AP7	56.50	409.940	116.80	0.9070	63.40
8.	AP8	67.50	489.130	110.20	0.9168	60.00
9.	AP9	67.75	521.154	89.60	0.9144	63.10
10.	AP10	60.00	387.077	72.00	0.9142	57.33

Table 3: Result of Thermogravimetric Analysis

T_{onset} (°C)	$T_{50\%}$ (°C)	$T_{degradation}$ (°C)	% Residue at 800 (°C)
350	630	700	8.0
254	420	490	6.8

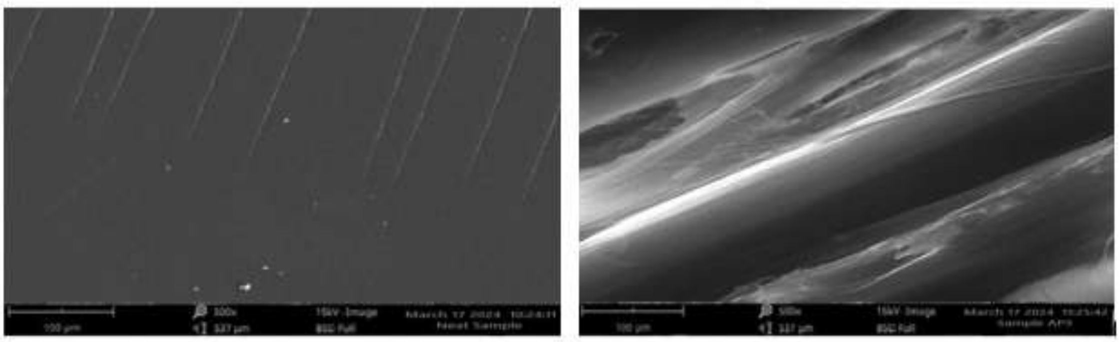

Plate IXa: SEM image for neat sample **Plate IXb:** SEM image for sample AP5

Figure 2: Scanning Electron Microscopy

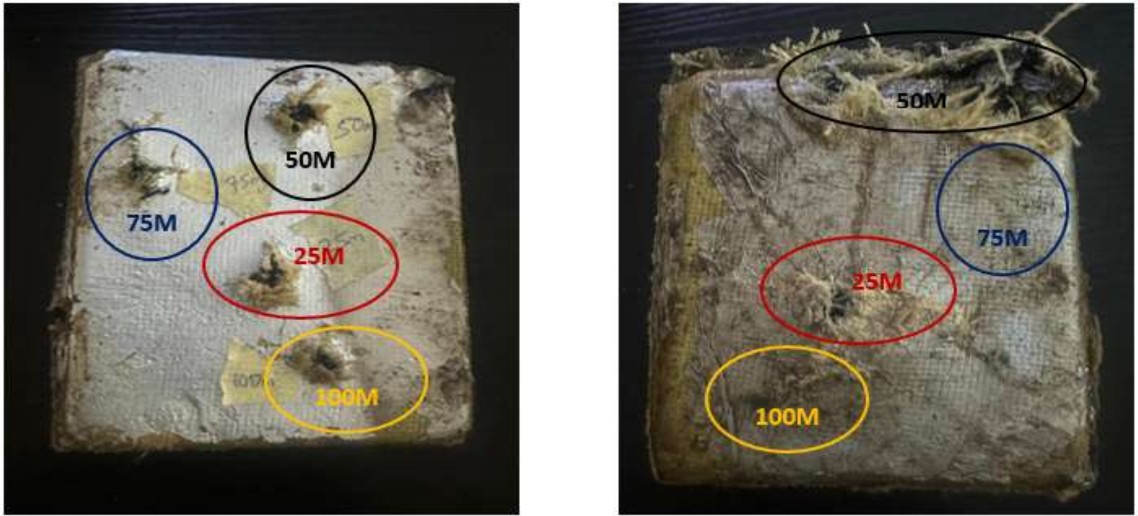

Plate Xa: Front view of tested produced ballistic plate **Plate Xb:** Rear view of tested produced ballistic plate

Figure 3: Ballistic Test Assessment

Analysis of the produced plate with an existing plate

Figure 4: Weight of Produced Plate **Figure 5:** Weight of Existing Plate

IV. DISCUSSION

The produced armor plate weight is 0.4 Kg while the weight of an existing one was 3.4Kg as shown in Figure 5 and 6 respectively. The length and breadth of both plates are 105 x 135mm and 250 x 300m respectively.

To determine the relative weight ratio between an existing plate sample and the produced plate sample, we need to compare their weight per unit area.
To calculate the Area of Each Sample
Area of existing Plate = 250 mm x 300 mm = 75,000 mm^2
Area of produced plate = 105 mm x 135 mm = 14,175 mm^2
To calculate the Weight per Unit Area
Weight of conventional plate per unit area= 3.4 kg/75,000 mm^2 = 0.0000453 kg/mm^2
Weight of produced plate per unit area = 0.4 kg/14,175 mm^2 = 0.0000282 kg/mm^2
To determine the Relative Weight Ratio
The relative weight ratio is given by:
Ratio = 0.0000453/0.0000282 = 1.61 approx.

This means the conventional plate sample is 1.61 times heavier per unit area than the produced plate sample.

Tensile strength is a measure of the maximum stress a material can withstand while being stretched or pulled before breaking. The results obtained indicate that sample AP5 has the highest tensile strength at 71.25 MPa, followed by sample AP4 at 70.00 MPa while sample AP7 has the lowest tensile strength at 56.50 MPa. The highest tensile value obtained from the tensile strength test of sample AP5 could be attributed to possible better mix ratio of Kevlar woven fiber to epoxy resinas evidenced by Tudu, 2013. However, the lowest value obtained for sample AP7 could be due to poor laminate interaction between the woven Kevlar fibre and epoxy resin which might have caused internal delamination of the sample and hence poor tensile strength. This attribute is usually caused by low lamination pressure during the composite formation. This has been reported by Josmin et. al., 2012 [10].

Tensile modulus, indicating a material's stiffness under tension. It's calculated as the ratio of stress to strain within the elastic range of a material. The neat sample has a tensile modulus of 328.962 MPa. Among the other samples, AP5 has the highest tensile modulus at 523.897 MPa, while AP3 has the lowest at 379.032 MPa. The tensile modulus values suggest that the Kevlar reinforce samples are stiffer than the neat sample, indicating increased stiffness due to the addition of Kevlar fiber to the neat sample.

Flexural strength test results which measure a material's ability of the produced Armor plates to withstand bending. The results show that AP5 has the highest flexural strength at 141.20 MPa, while AP10 has the lowest at 72.00 MPa. It is expected that the flexural strength of the Armor plates increased with increase Kevlar fiber due to flexible nature of the woven fiber as compared with glassy epoxy resin. However, when to or more materials are combined to form a composite, the resulting composite exhibits unique properties different from the individual component properties of the component materials. This could be attributed to the flexural results obtained for the produced Armor plates.

The results shows that sample AP5 also has the highest flexural modulus at 5.097 GPa, while AP10 has the lowest at 2.599 GPa. This results trend could also be attributed to the unique properties of composite different from its materials properties.

Impact strength is a crucial mechanical property that indicates a material's ability to withstand sudden impact or shock loading. It is often measured in terms of energy absorbed per unit thickness or area of the tested sample specimen before fracture and it’s represented as J/mm or J/mm^2. The neat sample has an average impact strength of 0.1858 J/mm. Sample AP5 stands out with an impact strength of 0.9364 J/mm, higher than other reinforce samples, suggesting better impact resistance and higher energy absorption capacity. However, samples AP1, AP2, AP3, AP4, AP6, AP7, AP8, AP9 AND AP10 show higher impact strengths than the neat sample, indicating potential brittleness reduction effect of Kevlar in composites as reported by Oboh et al [11].

Hardness property indicates the resistance of the plates to indentation. The neat sample has an average hardness of 55.90 Hv whereas sample AP4 has the highest average hardness at 71.57 Hv, while AP10 has the lowest at 57.33 Hv among other Kevlar reinforced samples. It is expected that as the Kevlar loading increases, the hardness properties of the produced Kevlar fiber reinforced epoxy resin composite decrease due to the fact that introduction of flexible material in a hard glassy matrix tends to reduced its hardness. This is evidence by the report of Malcenji et al., 2010 [12].

TGA is an analytical technique use for determination of thermal stability of material and its fractional volatile contents by observing the change in weight of the test specimen with increasing constant temperature rate of the test specimen. Three thermal regions that are usually associated with TGA include first, second and third region corresponding to drying (onset), decomposition and complete degradation respectively (Oboh et al., 2017) [13]. The onset temperature region defines the degradation temperature at which the test sample losses not more than 5% of its initial weight. This temperature is used to classify maximum service temperature of a tested sample and this defines the temperature the material will be exposed to without deforming during service life of the sample.

Table 1 indicates that the onset temperature is 254 ^{o}C and 350 ^{o}C for the tested neat sample and sample AP5respectively. Other important parameters that are obtained from the thermograph of TGA are $T_{50\%}$ which represents the temperature at which the sample has lost 50% of its initial weight. This is classified as the second region temperature of TGA curve and it describes the decomposition temperature of the tested samples into volatile (gaseous) and residues (solid) components. $T_{50\%}$ obtained are 420 ^{o}C and 630 ^{o}C for the neat sample andsample AP5respectively. $T_{degradation}$ is the third region of the TGA thermograph. This refers to the temperature at which maximum rate of degradation is obtained. This temperature region indicates that no volatile component is left in the sample but the residue. 490 ^{o}C and 700 ^{o}C were obtained as $T_{degradation}$ for the neat sample andsample AP5respectively.

Visahk et al., 2012 [14], reported that when composite materials are heated gradually from lower to higher temperature, moisture and other volatile components will get evaporated first, further heating of the material will get part of it degraded and converted into gaseous product with corresponding weight lost as observed in the TGA thermographs. Subsequently, further heating will remove all organic matters in the sample leaving behind only inorganic components as residue. This happens at complete degradation temperature which is defined as $T_{degradation}$ and the residue left of the sample is defined as % residue at this temperature which is 6.0 % and 8.1 % for the neat sample andsample AP5respectively.

Plate IXa and IXb are the surface morphology results of the neat (sample without reinforcement) and the best performed (sample reinforced with 25 % Kevlar fiber) samples of the produced armor plate composites. The surface morphology examination was carried out at the destructive surfaces of impact strength test specimens of the produced composite samples. The purpose of this investigation was to study the behavior of the composite plate under impactive force that resulted to the least and the best performance of the selected samples among others. A single phase of epoxy resin could be seen in plate 13a whereas the plate 13b indicates image of fiber pulled in the matrix as well as even fiber alignment along the impact force as the image revealed that fiber is concentrated along the failed region in the matrix'

The ballistic performance of a ballistic plate is determined by its ability to withstand impacts from various threats and ranges. Analyzing the results of the ballistic test performed on a 30mm thick plate at various firing ranges of 100m, 75m, 50m, and 25m against 7.62mm x 39mm ammunition from an AK-47 provides significant insights into its effectiveness against test ammunition 7.62mm x 39mm,commonly used in AK-47 rifles characterized by effective shooting range of approximately 300 meters.The results obtained as evident in plates Xa and Xb show no penetration was observed on the rear side of the plate at 100m and 75m shooting ranges. This is an indication that the developed ballistic plate exhibits strong stopping power and effectiveness at these ranges. The combination of thick material and possibly its composition (Kevlar fibre, epoxy resin and fire-retardant materials) effectively absorbs and dissipates the energy from the impact of the projectiles, preventing penetration. This suggests that the developed ballistic resistance plate meets or exceeds standard expectations for threats at these distances, offering significant protection for users in combat situations.

However, at 50m shooting range, a diverted exit was observed at the edge of the plate which is an indicative of laminate failure other than plate penetration. This result indicates that while the projectile did not penetrate fully, travel paths were altered due to the laminate structure of the plate. The laminate possibly absorbed the energy but failed to retain structural integrity at the edge, leading to a divergence of the projectile path. Consequently, at this range, the effectiveness starts to degrade, suggesting that while the plate can still provide some level of protection, the risk of failure increases, especially at the edges, where the material may generally be weaker or less able to absorb energy.

Also, at 25m shooting range, penetration was observed. At this closer range, the kinetic energy of the projectile is significantly higher due to reduced distance and the dynamics of energy transfer. The 30mm thickness of the plate was seems insufficient to stop the projectile, indicating a critical threshold at which the ballistic plate cannot adequately protect against impacts of this nature. This is a critical finding, as at 25m, the plate fails to provide protection, showcasing a clear limitation.

Conclusively, the developed ballistic plate from this research demonstrates high resistance at longer ranges (100m and 75m), indicating effective design against the AK-47's 7.62mm x 39mm round under these conditions. However, the performance degrades sharply at closer distances (50m and 25m). The critical threshold for this plate can be determined to be between 50m and 25m. The divergence of a bullet's path at the edge signifies a need to consider the potential for laminate failure in design evaluations. Therefore, it would be advisable for further research to explore methodologies to enhance performance, particularly focusing on edge reinforcement and material distribution to mitigate weaknesses at closer engagement ranges.

While the tested developed ballistic plate exhibits strong protective capabilities at moderate to long ranges, there are significant performance limitations evident at closer distances, underscoring the importance of thorough testing and design considerations in ballistic protection equipment. The ballistic plate is suitable for level IIA standard.

V. CONCLUSION

Based on the results obtained in this Research, the following conclusions were drawn:

i. High impact strength of Kevlar/Epoxy Resin composites were formulated, successfully devoloped and casted in moulds.
ii. Various mechanical properties tests were conducted and the result showed that AP5 has the best mechanical properties.
iii. The Armour plate was produced from AP5 which exhibit the best mechanical properties.
iv. Ballistic test was conducted on the produced plate at 25m, 50m, 75m and 100m. Produced plate sample has lower weight per unit area than conventional plate which will significantly reduce the overall load on the wearer, improving mobility and comfort.

5.1 Recommendations for future works

Although the main objectives of current research project are realised, there are still more work to be done for further improvement of protective Armor Plates. These include the following:

(i.) Dynamic impact behavior of closed cell aluminum foam composite armors made by impregnation of aluminum foams with Kevlar short fibers and nano-fibers should be studied. This study will allow to compare what fiber impregnation and what percentage can produce hybrid composites with the most improved resistance against ballistic impact failure.
(ii.) The effects of impregnation of shear thickening fluid, Kevlar short fibers and carbon nano-fibers into aluminum foam to produce new hybrid polymer composites materials need to be investigated. Conducting this investigation will enable the understanding of whether or not the impregnation of colloidal silica nanoparticles can produce a positive hybridization with Kevlar micro-fibers or carbon nano-fibers and epoxy resin in the manufacture of hybrid composites made of aluminum foam plates. The optimal configuration of the hybrid composite plates can be determined from the results of ballistic testing on the plates.
(iii.) Ballistic impact performance of hybrid composite armors made of aluminum foam/epoxy resin containing the dispersion of shear thickening fluid made of various synthetic nano-fillers of colloidal silica, silica carbide and gamma alumina. This study will determine whether or not such impregnation of nano-particles into aluminum foam can improve the impact resistance of aluminum foams. In addition, the results will allow to determine which nano-particles will provide better hybridization effect.

REFERENCES

[1] Institute for Economics & Peace Global Terrorism Index (2018): "Measuring the Impact of Terrorism". Institute for Economics & Peace; Sydney, Australia.
[2] Bhatnagar A. (2016); "Lightweight Ballistic Composites: Military and Law-Enforcement Applications. Woodhead Publishing; Cambridge, UK.
[3] Sarva S. (2007); The effect of thin membrane restraint on the ballistic performance of armor grade ceramic tilesInternational Journal Impact Engineering.
[4] Abrate S. (2005); Impact on Composite Structures. Ed. Revised. Cambridge University Press; Cambridge, UK: pp. 215–220.

[5] Lee Y.S., Wetzel E.D., Wagner N.J. (2003); The Ballistic Impact Characteristic of Kevlar Woven Fabrics Impregnated with a Colloidal Shear Thickening Fluid. Journal of Material Science 38:2825–2833. doi: 10.1023/A:1024424200221.

[6] Morye S.S., Hine P.J., Duckett R.A., Carr D.J., Ward I.M. (2000); Modelling of the energy absorption by polymer composites upon ballistic impact. Composite Science Technology 60:2631– 2642. doi: 10.1016/S0266-3538(00)00139-1.

[7] Hazell P. (2015); Armour: Materials, Theory, and Design. CRC Press/Taylor & Francis; Boca Raton, FL, USA.

[8] Benzait S., Trabzon L. (2018); A review of recent research on materials used in polymer–matrix composites for body armor application. Journal of Composite Material 52:3241–3263 doi: 10.1177/0021998318764002.

[9] Kumar V., Singh J., Kumar R., Chaudhary V. (2019) Effect of Hot Air Oven Drying on the Moisture Kinetics and Drying Rate of Osmo-Dried Papaya (Carica papaya L.) Slices.

[10] Josmin, P, Sant, K, Sabu, T, (2012): Advances in polymer composites. Journal of Polymer Engineering Vol 1, Pp 2.

[11] Oboh, J.O., Eli musa2, Ikhouria, Mohammed, I. B4., Okele, I.A5., Zango, L. Y. and Marut, A. J. (2015)" Characterization of Date Palm Seed (Phoenix Dactylifera) for the Preparation of Polypropylene/ Particulate Date Palm Seed Composite.

[12] Malcenji k. Goodship V., Christmass P., Smith G. F and Pearce B., (2010); "A mixed plastic waste and de-inked residue composites from recycled paper waste products" progress in rubber plastics and recycling technology, vo. 26 (No. 2), pp. 93-106. ISSN 1477-7606.

[13] Oboh JO., Okafor JO., Kovo AS., Abdulrahman AS. (2017): "Investigation of eco-friendly cellulosic nanoparticles potential as reinforcement agent in the production of natural rubber composites" Nigerian journal of technology, Vol. 16, No. 4. Page 15.

[14] Visakh, P.M, Thomas, S. Oksman, k., and Mathew, A.P. (2012a). Cellulose nanofibers and cellulose nano whiskers based natural composites: Diffusion, sorption, and permeation of aromatic organic solvents, Journal of Application of Polymer Sci 124, 1614-1623.