

Development of Wood-ash/Resin Polymer Matrix Composite for Body Armour Application

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Abstract— This research work formulated and developed a polymer matrix composite (PMC) for body armour application by adopting hand lay-up processing method in producing the epoxy resin-wood ash composite. The usual waste from wood after combustion, wood ash, was used as the additive in the development of the PMC. Chemical composition of the prepared wood ash was determined using X-ray fluorescence spectrometry. The mechanical properties of the developed PMC was evaluated and discovered to have been enhanced through the inclusion of the wood ash particles. 2.3% inclusion of wood ash resulted in the tensile strength value of 104 N/mm² against 86 N/mm² for neat reinforced resin. The impact strength of the PMC increased from 50 J/mm² (without wood ash) to 112 J/mm² while 25.4 HRF was recorded for the hardness value of the PMC with wood ash against 23.4 HRF for the neat reinforced PMC. The microscopic analysis also revealed that the wood ash particles were uniformly distributed in the matrix without indication of segregation. When subjected to ballistic tests, the developed PMC successfully arrested the 9 x 19 mm ammunitions after perforating some layers of the sandwiched sample. The research is therefore applicable for the protection of torso.

Keywords— Armour, Composite, Fibres, Polymer, Wood ash

1 INTRODUCTION

THE term body armour is usually associated with vests designed to provide ballistic protection to the vital organs in the torso (NIJ, 2014). Torso is the main part of the body, not including arms, legs or head. Usually, a vest contains two armour panels held in place by a carrier. One panel protects the front of the torso, the other protects the rear. To protect the sides of the torso, the vest is worn with the front panel overlapping the rear panel. These panels can typically, but not always, be removed from the carrier. A soft armour panel works much like a baseball catcher's mitt. When a handgun bullet strikes the panel, it is caught in a "web" of strong fibres. These fibres absorb and disperse the impact energy that is transmitted to the panel from the bullet. This process causes the bullet to deform or "mushroom" (NIJ, 2014).

Various materials are employed for these armour development: metals, polymer, ceramics and composites. Most times engineers are faced with the task of developing a new material that has light weight, low cost and good mechanical properties (Nnaji, 2012). Presently, composites are increasingly being used in aerospace, naval and automotive applications due to their high strength and stiffness to weight ratio (Samant, 2013). Composite material is a heterogeneous solid consisting of two or more different materials that are mechanically or metallurgically bonded together. Each of the various components retains its identity in the composite and maintains its characteristic structure and properties. The composite material, however, generally possesses a unique combination of properties, such as stiffness, strength, weight, that is not possible with the components by themselves (Sanusi *et al.*, 2013). Epoxy resins are the most commonly used thermoset plastic in polymer matrix composites. Epoxy resins are a family of thermoset plastic materials which do not give off reaction products when they cure and so have low cure shrinkage.

They also have good adhesion to other materials, good chemical and environmental resistance, good chemical properties and good insulating properties (Saleh, 2014). Additives such as plasticizers, thermal and light stabilizers, flame-retardant agents, fillers, colorants, processing aids, impact modifiers, and biocides are added to polymeric composites to improve desired mechanical properties (Sanusi *et al.*, 2013).

Nnaji (2012) developed rice husk ash with epoxy that could be utilized for composite production in areas subjected to tension and abrasion as an extender filler to reduce cost and minimize environmental pollution. However, he found that porous structure of rice husk ash, poor dispersion and poor interfacial adhesion (bonding) between the rice husk ash and the epoxy matrix caused decrease in flexural strength, toughness and hardness as percentage of rice husk ash fillers increased. He concluded that rice husk ash is not a good reinforcement material.

Saleh *et al.* (2014) formulated composite by using Epoxy resin and Fly ash with Silica fume as the filler. Samples were prepared by hand-made moulds and adding each filler separately with different ratios. Then the mechanical properties of these material (tensile, hardness, compression, impact and bending properties) were studied. They discovered that the increase of additive ratios of fly ash led to increase of compression strength, tensile strength and hardness but showed decreasing in bending strength.

Traditionally, armour was typically made of monolithic high strength steels to protect against conventional projectile threats. However, the high density of steel makes it undesirable for personnel protection (Roy, 2011; Guild *et al.*, 2007). More advanced armour materials make use of layering techniques comprised of composite structures. Examples include Kevlar Fiber-Reinforced Polymers (KFRP), Carbon

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ylene woven fabric composites (Roy, 2011).

An encouraging possibility to the formulation of polymeric composite is to use a low density additive particulate material like wood ash, a by-product of combustion of wood, in a polymer matrix to form a high impact PMC for the protection of security personnel and other individuals that deserve wearing it. Also, the ability of armour to stop bullets, its "ballistic resistance", cannot be discerned by inspection; it must be inferred from the results of tests in which sample armour is shot (Silva, 2014; U.S. Congress-OTA, 1992). It is on this premise that this work carried out a comprehensive ballistic resistance test on the developed PMC material according to military standard, MIL-STD-662F-1997 (V_{50} ballistic test for armour), while utilizing the common household waste in an average Nigerian home (wood ash) as the additive in the formulated PMC.

2 EXPERIMENTAL PROCEDURES

The following raw materials were used for the research work: Wood ash particles, commercial epoxy resin, tetraethylenepentamine, fibre glass, acetone, natural rubber, high density polyethylene (HDPE), sulphur, mecaptopbenzothiazole (MBT), glass powder and trimethylquinolone (TMQ).

2.1 Preparation of Wood Ash

500g of woodchips (hard wood) was collected. The woodchips were pyrolyzed by heating to 400°C in an electric oven. At the termination of devolatilization, the container lid placed in the oven was removed and the residual char was allowed to burn at 350°C for 5hrs. Thereafter, sample for X-ray fluorescence spectrometry was prepared. It was finely ground and poured in a glass tube to hold the wood ash on to sample compartment of the equipment for analysis.

2.2 Formulation of Polymer Matrix Composite (PMC) Sample

A hand lay-up processing method was employed (Manoj and Vikas, 2010). Liquid epoxy resin, 3g, was thoroughly dissolved in 5ml of acetone. The dissolved epoxy resin was then homogenously mixed with 0.5ml of tetraethylenepentamine that served as the curing agent. Thereafter, optimized 2.3% by weight wood ash from our previous work (Sanusi et al., 2013) was evenly mixed with the prepared resin-tetraethylenepentamine mixture. The mixture was then poured on 10g of fibre glass (reinforcement) placed in a petri-dish. This was allowed to cure naturally for 24 hours and later transferred into vacuum electric oven for even curing for two hours at temperature of 60°C to attain even curing of the samples. Following this procedure, all the polymer matrix composite (PMC) samples were prepared and further processed for various experimental analyses.

2.3 Layering Process

The formulated polymer matrix samples described in section 2.3 have an average thickness of 5mm. To meet the minimum standard thickness of 10mm required for the impact test and 20mm thickness targeted for the ballistic test, sandwiching of the layers of produced polymer matrix was

adopted yielding impact specimen geometry. For the ballistic specimen, 100mm by 100mm by 20mm was sandwiched.

2.4 Compounding Process

This process was aimed at producing a unit specimen that would prevent delamination of sandwiched composite layers for ballistic test. This was achieved by blending natural rubber, high density polyethylene (HDPE), sulphur, mecaptopbenzothiazole (MBT), glass powder and trimethylquinolone (TMQ) according to the percentages indicated in Table 1. The formulation was prepared by heating the raw materials to a temperature of 170°C in an electric oven and then blended thoroughly using 2-high rolling machine. It was then pressed into a sheet-form using compression moulding machine. The specimens were then wrapped with the sheet forming an additional thickness of about 3mm around the rectangular surfaces of the fabricated composite. The samples were then placed in a prepared metallic (steel) mould (Fig. 1) where they were pressed using hydraulic press at a temperature of 150°C and pressure of 15bar.

2.5 Sample Preparation for Tensile and Impact Tests

The compounded material were taken out of the mould and then carefully machined to standard geometry of 12.6mm by 3.6mm by 80mm for tensile test (ASTM D638, 2014) and 10mm by 10mm by 100mm for impact test (ASTM D6110, 2010).

Table 1. Raw Materials Composition for Compounding Process

Material	Composition (% Wt.)
High Density Polyethylene (HDPE)	56.4
Sulphur	0.5
Nitrile-butadiene Rubber (NBR)	24.1
Mecaptopbenzothiazole (MBT)	1.6
Glass powder	16.1
Trimethylquinolone (TMQ)	1.2

Source: Chemical and Leather Research Laboratory, Zaria (2012)

2.6 Mechanical Tests

The maximum tensile load that could be applied before the developed PMC fractured was determined by tensile test in accordance with ASTM D638 (2014). The impact value was determined in accordance with ASTM D6110 (2010); a 25J of load was released at a velocity of 5.24 m/s on the specimens while the energy dissipated before fractures were recorded. The hardness of the specimen was measured in accordance with ASTM D785-08 (2008) standard method of measurement.

2.7 Ballistic Impact Tests

Ballistic (firing) test was carried out on the developed composite in order to ascertain the potency of the developed PMC sample plate against the projectile (Guild *et al.*, 2007). It was carried out at the Shooting Range: weapon/ammunition testing section of the Defence Industries Corporation of Nigeria (2015) which has the facilities that is represented schematically in Fig. 2. The ammunition used for the ballistic test is 9 x 19 mm (Plate 1). The test weapon (sub-machine gun) was supported, levelled and positioned. Thereafter few pre-test rounds were fired through the witness plate to determine the point of impact. Then the developed PMC specimen on the support fixture was placed 5m and 10m from the test weapon. The witness plate was placed 15cm beyond the test specimen as shown in Fig. 2.

2.8 Microstructural Examination

The microscopic analysis (using electron microscope-JSM 5900LV) of the post mechanical tests were carried out to observe the distribution of wood ash particles in the matrix, resin-wood ash interface, glass fibre distribution in the matrix, glass fibre-matrix interface and deformation behaviour. Small fractured composite sample from impact test analysis was collected in a cleared and cleaned petri-dish and carefully study under an electron microscope.

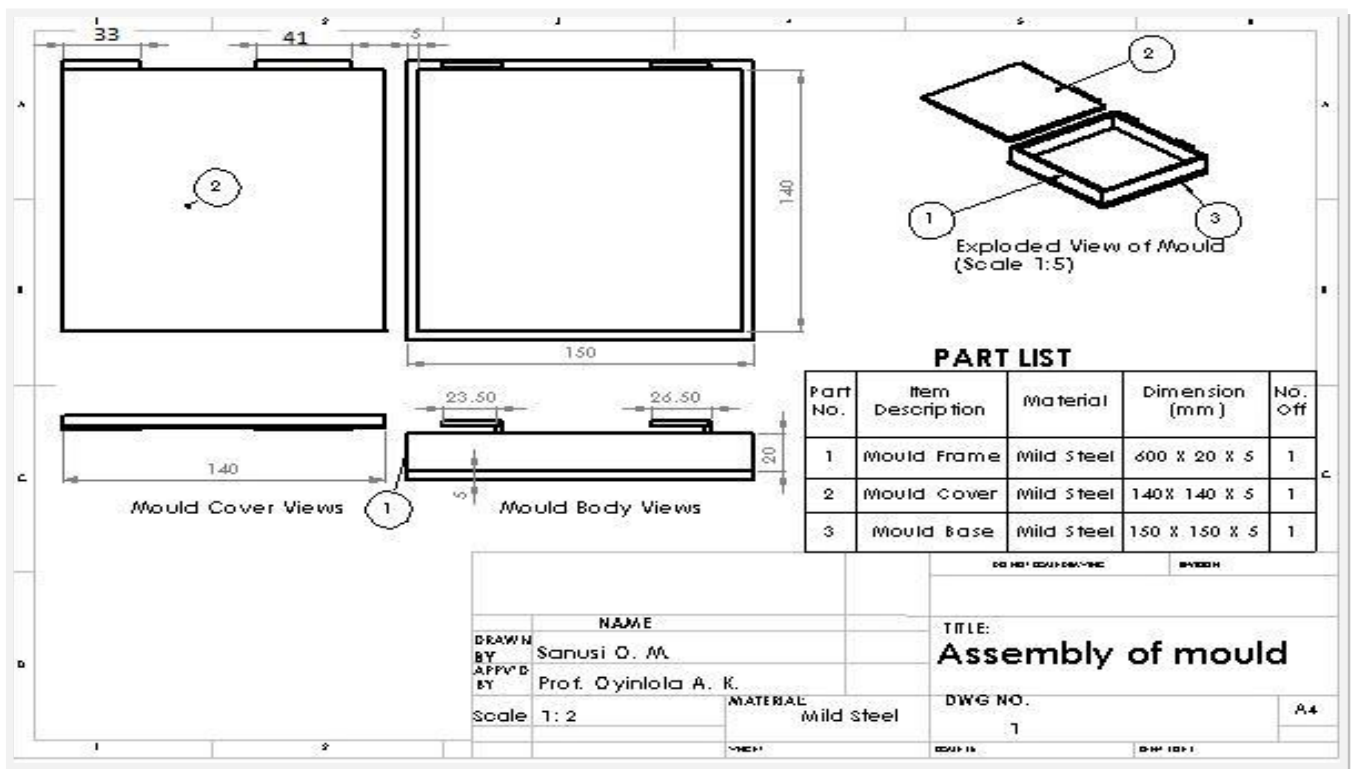


Fig 1. Details of Mould Used for Compounding Process

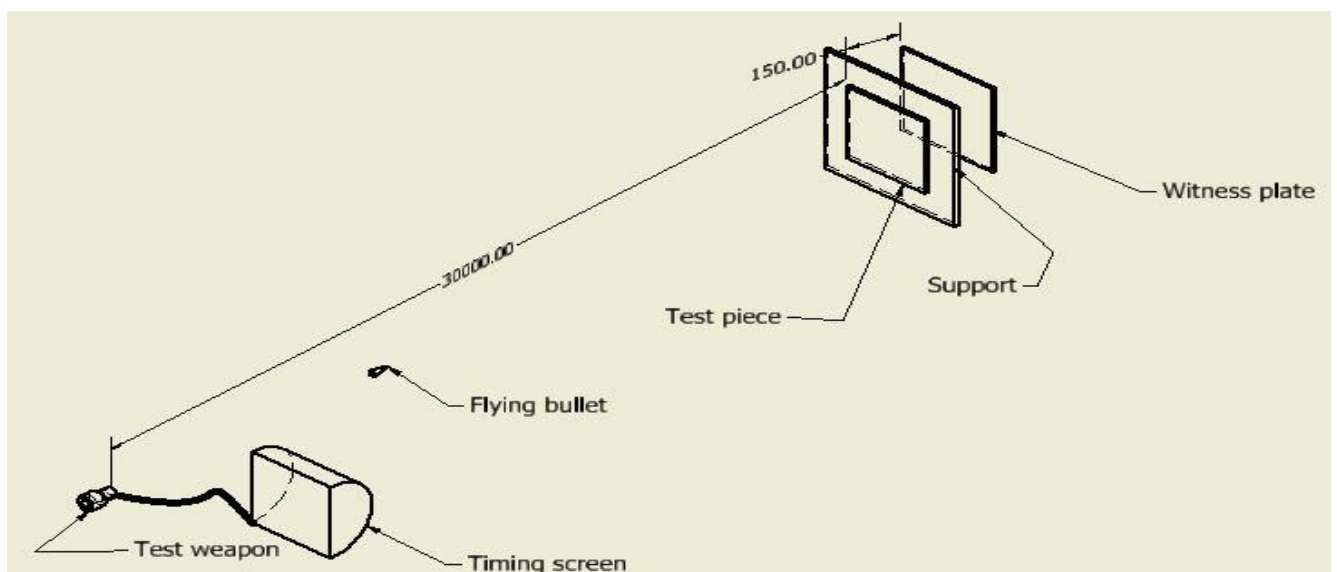


Fig 2. Ballistic setup at DICON shooting range

Then bullet weight, range/distance and velocity necessary in ballistic experimental procedures (MIL-STD-662F, 1997) were observed and ensured before shooting with weapon system in accordance with MIL-STD-662F (1997). The plate was firmly clamped at 0° obliquity to the bullets.



Plate 1. 9x19mm ammunition (ball and the assembled bullet) used for the ballistic experiment

3 RESULTS AND DISCUSSION

3.1 Chemical Analysis of Wood Ash

The chemical compounds present in the prepared wood ash was analyzed using X-Ray Fluorescence Spectrometry (WDXRE: Mini Pal4 ED-XRF); the result is shown in Table 2.

Table 2. Chemical Composition of Wood Ash

Compound	Concentration (% Wt)
CaO	78.50
K ₂ O	8.79
SiO ₂	7.20
SO ₃	1.10
TiO ₂	0.31
MnO	0.09
Fe ₂ O ₃	1.27
ZnO	0.06
Y ₂ O ₃	1.20
BaO	1.00
CeO ₂	0.04
Eu ₂ O ₃	0.05
Re ₂ O ₇	0.30

The three major compositions in the wood ash are: CaO (78.5%), SiO₂ (7.2%) and K₂O (8.79%). This establishes a basis of testing the potentiality of wood ash as an additive for polymeric composite as it contains some major chemical compounds in common with fly ash additive as reported by Manoj and Vikas (2010) in developing polymer matrix composite. The presence of CaO, SiO₂ and K₂O can improve the fire resistance of the developed PMC due to their high melt-

ing points. Silica (SiO₂) has a density of 2.648 g cm⁻³ and melting point of 1600-1725 °C (Ebbing and Gammon, 2005). Calcium oxide (CaO) has a density of 3.5 g cm⁻³ and melting point of 2572 °C (Ebbing and Gammon, 2005). Potassium oxide (K₂O) has a density of 2.35 g cm⁻³ and melting point of 350 °C. This can also aid the ballistic performance of the developed PMC.

3.2 Mechanical Tests

The formulated polymer matrix composites (PMCs) with its respective mechanical properties is depicted in table 3. The formulated sample PMC2 (2.3% inclusion of wood ash, 22.7% resin and 75% fibre glass) resulted in the tensile strength value of 104 N/mm²; this is opposed to neat reinforced resin with 86 N/mm². Also the inclusion of wood ash led to significant increase in impact strength from 50 J/mm² (without wood ash) to 112 J/mm². 25.4 HRF was recorded for the hardness value against 23.4 HRF recorded for the net resin- fibre PMC.

Table 3. Formulated PMCs with the Mechanical Properties

Sample	Wood ash (%)	Epoxy resin (%)	Fibre glass (%)	Tensile Strength (N/mm ²)	Impact Energy (J/mm ²)	Hardness (HRF)
PMC1	0.0	23.0	77.0	86	50	23.4
PMC2	2.3	22.7	75.0	104	112	25.4

3.3 Ballistic Study

As earlier mentioned in section 2.7, this was carried out on the plate in order to ascertain the resistance strength of the PMC against the projectile; as shown in Plate 1. As shown in table 4, the test PMC specimen placed at 10 m from the test weapon shows that the bullet was stopped by the third PMC layer after perforating two layers (10 mm). After reducing the range to 5 m, the bullet was able to penetrate through three layers and consequently stopped and deformed to button-shaped by the fourth layer as depicted in the Plate 2.

Table 4. Ballistic Test Result

Shot	Bullet weight (g)	Distance (m)	Velocity (m/sec)	Pass/Fail
1	7.45	5	390	pass
2	7.45	10	390	pass

3.4 Microscopic Study of the Fractured PMC

Microscopic study revealed that wood ash particles are uniformly distributed in the matrix; there was no sign of wood ash particle segregation in the matrix. The resin-wood ash interface and glass fibre-matrix interface showed compatibility of the constituent materials in the fabricated PMC; as shown in Plate 3. This result is comparable to the work of Manoj and Vikas (2010). The reinforcement phase is the light-yellowish background, epoxy matrix has the reddish

background while presence of irregularly shaped wood ash particles is reflected in the whitish-yellowish region.

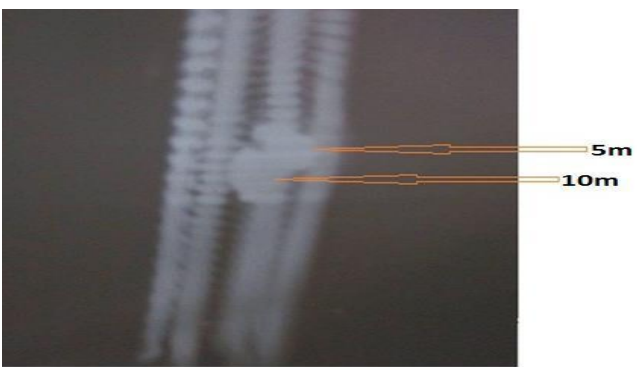


Plate 2. X-ray photograph of 9x19mm bullet stopped at 5m and 10m ranges (Bullet penetrated via left side of the plate)



Plate 3. Micrograph showing the compatibility of the constituent materials in the fabricated PMC (X200)

4 CONCLUSIONS

The following key conclusions were drawn from the research work:

1. Physically, the developed material was compacted without any observable separation of the constituent materials. Also, the microstructure study revealed that the developed polymer matrix composite using wood ash (additive) have good interfacial relationships with the matrix and the fibre glass reinforcement; as there was no mark of wood ash segregation in the formulated composite.
2. As the composite arrested and deformed the bullets, the developed polymer matrix composite plate can be said to be effective in stopping 9 x 19 mm ammunition.
3. Due to the improved mechanical properties (strength: 104 N/mm²; impact energy: 112 J/mm²; and hardness: 25.4 HRF), the identified areas of body armour

applications of the developed PMC include bullet vest, anti-mine shoes, fire resistance jacket, military helmet.

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