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Short communication

Eggshell nanoparticle reinforced recycled low-density polyethylene: A new material for automobile application

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ABSTRACT

Waste from low-density polyethylene products after lifespan accounts for 70% of solid waste in most dumpsites, contributing to environmental impacts. Eggshell foul smells are threat to human and animal health. Prior to this study, there is no research documentation on transformation of both wastes into green composites for engineering applications. In this work, composites were developed using recycled low-density polyethylene (RLDPE) and eggshell Nanoparticles. They were evaluated structurally and mechanically. Straining which affirms an improvement in the load bearing capacity of the RLDPE due to incorporation of eggshell Nanoparticles was established by the composite XRD peak broadness. Structural integrities of the composites were confirmed with SEM. Maximum tensile strength was noted at 10% eggshell Nanoparticle additions to the RLDPE equal to 68% increase. About 52 and 19% enhancements in respective flexural strength and hardness value with 0.85% reduction in impact energy were noted at 12% eggshell Nanoparticle additions. Probability value, 0.0481 < 0.05 established significance of the mono-variate regression model to an estimation of the tensile strength of RLDPE/eggshell Nanoparticle composites and the model has 92.7% confidence. A bumper fascia prototype was fabricated from RLDPE/10% eggshell Nanoparticle composite possessing 10.64 Nmm^{-2} tensile strength, 21.964 Nmm^{-2} flexural strength, 21.69 J impact energy and 59 VHN hardness value using sheet forming technique. Therefore, future usage of the developed RLDPE/10% eggshell Nanoparticle composite is established.

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1. Introduction

Polyethylene is a thermoplastic material. It possesses properties favourable to many applications forming bases for its uses in many artefacts (Bello and Kolawole, 2020). Low density polyethylene (LDPE) products after life span account for 70% of solid wastes in many dumpsites. Wide applications of LDPE frequently come with environmental issues. Unfortunately, there are many industries that can handle the waste for producing new artefacts but this is not fully implemented, either due to indiscriminate dumping of polyethylene products, making it unavailable to many industries, limitation/absence of research documentations comparing properties of RLDPE with those of virgin low-density polyethylene (VLDPE) which will affirm reusage of the LDPE wastes. Although some studies were reported on RLDPE examining different properties, none of those researches (Atuanya et al., 2011, 2014a, 2014b; Agunsoye and Aigbodion, 2013) compared RLDPE properties with those of VLDPE composites. Moreover, use of bagasse (Agunsoye and Aigbodion, 2013), breadfruit seed hull (Atuanya et al., 2014a), bean pod (Atuanya et al., 2014b), wood (Atuanya et al., 2011) and peanut husk (Obasi, 2015) were reported for modifying RLDPE. Moreover, eggshell report was found on RLDPE (Abdulrahman and Haruna, 2015), high density polyethylene (Sutapun et al., 2013; Oladele et al., 2019) and polypropylene (Dhaliwal and Kapur, 2013). Based on the cited literature, there

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is a documented study on the use of 75 μm sized eggshell microparticles as RLDPE reinforcement. Hence there is a need for this research to contribute eggshell nanoparticle as RLDPE reinforcement to literature. Therefore, development of nanocomposites from RLDPE and eggshell nanoparticle (76.25 nm) is novel since no report on this attempt is found in literature before this study.

Improper management of eggshell contributes to environmental problem (Hassan and Aigbodion, 2015). Precisely, foul smells from eggshells are threat to human/animal health. Huge amounts of eggshells from hatcheries/fast food industries are delivered to grounds daily. Some industries spend huge amount on their disposals whereas they are important materials for some applications. Ca^{2+} from eggshell solution was used for removing heavy metal from impure water (Tizo et al., 2018). Use of eggshells as a partial replacements for cement was established (Gowsika et al., 2014). Being a source of $CaCO_3$ which is a hard mineral, eggshell Nanoparticles (ESp) are potential reinforcement for improving RLDPE properties. Being light, RLDPE composites may be used as an automobile component. Automobile lightweight technology reduces CO_2 emission and improves fuel efficiencies (Belingardi et al., 2017). Use of 50% carbon fibre reinforced plastic (CFRP) was reported with 20% reduction in aircraft weight (Kobayashi, 2006). Full scale CFRP test for front panel of a passenger car was reported with 200 kg reduction in overall weight of the car equal to 8.85%/7gCO_2 reductions in car weight/per km driven (Kobayashi, 2006; Rowe, 2012). Therefore, this research was focused on developing RLDPE/ESp composite with their properties evaluations to establish their future applications.

2. Materials and methods

2.1. Synthesis and characterisation of eggshell nanoparticles

Eggshell nanoparticles were produced by manual crushing, disc grinding and 70 h ball milling in line with (Bello et al., 2015). Particles obtained at 70 h of milling were analysed using a multipurpose field emission transmission electron microscope (TEM) with attached energy dispersive X-ray spectroscope (EDX), Model: JEM 2100F.

2.2. Development of recycled low-density polyethylene composites

Materials used for composite productions are RLDPE, Saudi Arabia TASNEE VLDPE, absolute ethanol and 76.25 nm sized ESp. In developing RLDPE composites, 2 wt% (2 wt%) ESp were first dissolved in absolute ethanol, agitated for 20 min in a 2 kg-capacity tumbler ball mill to break up the agglomerates. Then, the RLDPE was added to ESp-ethanol mixture in the tumbler ball mill and stirred. After mixing, the mixture was heated while stirring at 80C until ethanol molecules were completely vapourised. Then, palm kernel oil used as plasticizer was added and the mixture was stirred. The mixture was processed using a two-roll polymer mill setting to 150C to soften and fabricate RLDPE/ESp composite sheet. Composite sheets were hot pressed at 90C and 0.5–1.5 Nmm^{-2} using hydraulic compression moulding and cavity moulds to produce various samples for analyses. The process was repeated with increasing wt% of ESp up to 12 wt% and some samples of VLDPE/ESp composites were also produced.

2.3. Structural examination on the composites

Representative samples of RLDPE/ESp composites were analysed by EMPYREAN PANalytical diffractometer with Pixcel detector having Bragg-Bretano geometry in continuous operating mode and automatic divergence slit type using Cu Kα radiation emitted from Cu anode material at an accelerating voltage of 45 kV and current of 40 mA. Morphology of the RLDPE composites was examined using ASPEX 3020 SEM equipped with the EDX.

2.4. Tensile test

Samples ($80 \times 6 \times 6$ mm^3) of RLDPE composites were subjected to uniaxial loading, causing gradual stretching of the examined sample at a strain rate of 0.001 per second until fracture occurred. Testomeric testing machine (Machine no: 0500-10080) of Rect 5 kN was used for the analysis per ASTM D 638–14 (ASTM D638–14, 2014) with modifications.

2.5. Flexural test

$120 \times 10 \times 6$ mm^3 rectangular RLDPE/ESp samples were subjected to 3-point bending test. The samples were placed horizontally on two pivots at 60 mm apart (span length) and loaded perpendicularly at the centre using the Testomeric testing machine. The analysis was carried out at room temperature, 18 °C and 50% humidity per ASTM D 7264-7264M-15 (ASTM D7264/D7264M-15, 2015) with modifications. The flexural strength, deflection and modulus were estimated automatically by the tester.

2.6. Impact energy test

In additions, impact energies of $75 \times 6 \times 6$ mm^3 RLDPE/ESp samples, notched to a depth of 2 mm at an angle of 45° were determined using Hounsfield balanced Izod impact machine (Serial no: 3915) at the Materials Science and Engineering Department, Obafemi Awolowo University, Ile Ife, Osun State, Nigeria. Before the test, the pendulum was released to set the scale to zero and each sample was stricken with a pendulum hammer released at a speed of 3.8 ms^{-1}. The impact energy test was performed per ASTM D256-10(2018) (ASTM D256-10(2018), 2018). Three different samples per each weight fraction were analysed in each of the mechanical investigations. Average value was estimated for each property at each weight fraction to ensure result accuracies. Their standard deviations were calculated and used as error bars.

2.7. Mono-variate regression analysis

Using tensile strengths as a dependent variable and a weight fraction of ESp as independent/predictor variable, a mono-variate regression model using 4th degree polynomial fitting was developed to predict values of tensile strength within the scope of experiment. OriginPro 8.5 software was used for the analysis. The model was diagnosed using ANOVA, regression coefficient of determination (R^2), Fishers, Probability value and validated with experimental data not included in developing the model. 4th degree model was chosen due to its highest R^2 and lowest probability value compared with those of other models after several trials.

2.8. Prototyping the automobile bumper fascia

An automobile bumper fascia prototype was fabricated using hot press. The mould was designed using Solidwork version 2018. The geometric models of the mould parts were converted to polylactic acid patterns using Creality Ender 3 Fused Deposition Modelling 3D printer at XreMechanics Academy, Ganmo, Ilorin, Nigeria. The pattern was used for preparing sand mould for casting the Al-Si mould parts for forming the prototype.

3. Results and discussion

3.1. X-Ray profiles of eggshell particles reinforced recycled low-density polyethylene composites

100% $CaCO_3$ was found in ESp (Fig. 1a). Moreover, RLDPE contains ethylene ammonium perchlorate hemihydrate ($C_2H_{11}Cl_2N_2O_{8\cdot5}$), polyethylene urea ($C_{14.76}H_{41.52}N_{12}O_6$) and cyclohexaamylose ($C_{36}H_{60}O_4$). $C_2H_{11}Cl_2N_2O_{8\cdot5}$ appears at positions (2theta) of 23.7°, 27.3 and 32.1°; $C_{14.76}H_{41.52}N_{12}O_6$ at 27.3° and $C_{36}H_{60}O_4$ at 32.1° (Fig. 1b). $C_{14.76}H_{41.52}N_{12}O_6$ and $C_2H_{11}Cl_2N_2O_{8\cdot5}$ are attributed to polyethylene molecules and amine compound added to the polyethylene to enhance its flame retardants while $C_{36}H_{60}O_4$ could be linked with palm kernel oil used as plasticizers. After addition of ESp to the RLDPE, potassium calcium fluoride (KCaF3) at positions, 23.12, 25.82, 27.57 and 31.71°; 3-p-toluyl-1, 2,2-trimethylcyclopentane carboxylic acid ($C_{17}H_{22}O_3$) at 23.12°; *cis*-9-octadecenoic acid ($C_4H_3Cl_3O_2$) at 25.82° and calcite ($CaCO_3$) at 31.71° were detected (Fig. 1c). The new compounds found with RLDPE/ESp composites confirmed chemical reactions between RLDPE (matrix) and ESp (reinforcement) while some of calcite from ESp were retained in the RLDPE/ESp composite. By comparing structural parameters as shown in Table 1, there was a shift corresponding to 2.4, 5.4 and 14.1%, respectively in the first, second and third peak positions with an appearance of a new peak at 31.71°, justifying variations in full width half maximum (FWHM) and d-spacings. FWHM of the first and second peaks remain the same while greater FWHM values of the third and fourth peaks imply that the peaks appear much broader when compared with others. This is demonstrated in Fig. 1d as the blue RLDPE diffractogram peaks submerge in red RLDPE/ESp diffractogram peaks. Peak broadness refers to particle refinement in comminution process (Zhang et al., 2015) while in composite technology, it implies straining of composite structure due to addition of ESp (Speakman, n.d.). Presence of ESp between the RLDPE molecules shortens the distance of a RLDPE molecule from another, explaining smaller values of RLDPE/ESp d-spacings. This affirms a composite's closed packed structure.

3.2. Microstructural properties of eggshell particles reinforced recycled low-density polyethylene

Average of sizes of individual ESp determined using a scale of 0.57″ (blue line) from Microsoft word to represent 100 nm resolution (red line) from the TEM image is 76.25 nm, affirming use of eggshell Nanoparticles as reinforcement in this study. Agglomerates in Fig. 2a was addressed by dissolving ESp in absolute ethanol to break up agglomerates prior to mixing with the polyethylene. Energy dispersive X-ray spectroscope shows that ESp possess Ca, C, K, O and Cu (Fig. 2a). Presence of C and O affirms that metals present in ESp exist in minerals like $CaCO_3$, K_2CO_3 and $CuCO_3$ rather than free elements. Tallest peak belonging to Ca confirms that eggshell contains mainly $CaCO_3$, already established in Fig. 1a. Pristine RLDPE appears as a continuous solid body developed from fusion of numerous polymeric grains during processing. Polymeric grains of different colours characterise the pristine RLDPE. The white regions represent some polyethylene grains/phases having fibrous, polygonal and irregular shapes firmly connected together affirming structural continuity of the pristine RLDPE. Differences in colour can be linked with phases of varied chemical formulas confirmed with the pristine RLDPE by XRD in Fig. 1b. Carbon having tallest peak was established by EDX as only element present in RLDPE. Beside C, H is expected to be found in the RLDPE. It is not detected perhaps due to its lightness. At 10 wt% ESp addition to RLDPE, morphology of the composite has many tiny grains of varied geometries fused together to form a continuous rigid structure without any structural imperfection (Fig. 2c). Morphology of a portion of the RLDPE/10%ESp at 6000 magnifications (Fig. 2d) affirms high structural integrity as the structure appears in layers without any ESp segregations/clusters. About 49% C, 20% O and 16% Ca (Fig. 2c)

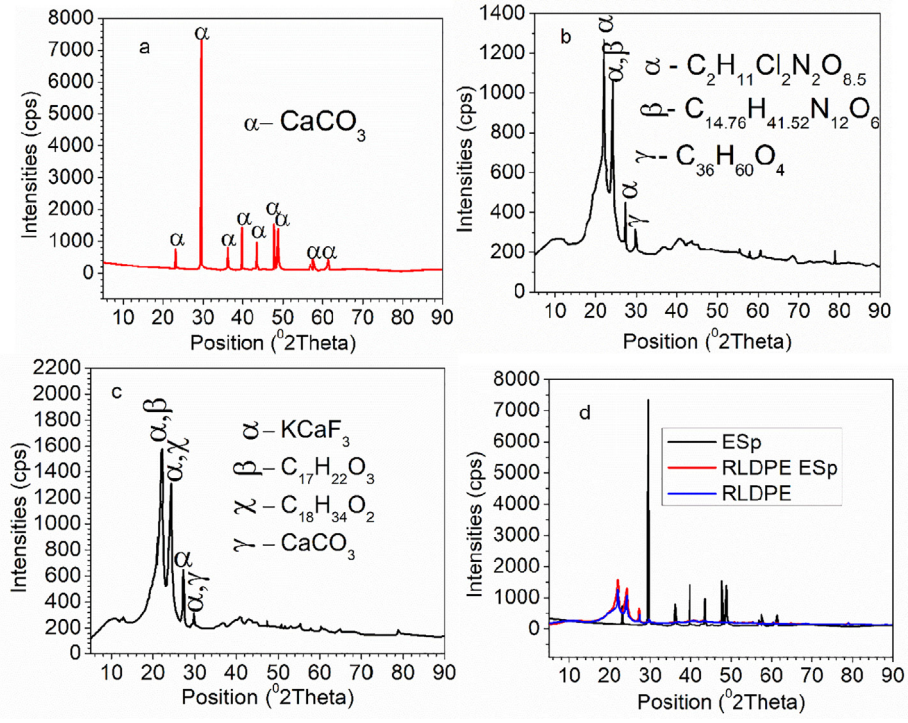


Fig. 1. X-ray diffractograms of (a) eggshell Nanoparticles (b) recycled low-density polyethylene (c) recycled low-density polyethylene/eggshell nanocomposites (d) all materials in superimposed form.

Table 1
Structural parameters of recycled low-density polyethylene (RLDPE) and.

S/N	Positions (2theta)		Full width half maximum (°)		Interplanar spacing (Å)	
	RLDPE	RLDPE/ESp	RLDPE	RLDPE/ESp	RLDPE	RLDPE/ESp
1	23.7	23.12	0.3	0.3	3.75	2.6
2	27.3	25.82	0.3	0.3	3.27	2.09
3	32.1	27.57	0.3	1.64	2.79	1.87
4		31.71		2.23		1.77

are attributed to RLDPE and ESp which are the main raw materials for developing the composites. Other elements are linked with minor phases in ESp and the additives to the RLDPE. Various compounds detected by XRD in Fig. 1c affirm C, O, Ca and K while compounds of Si, Mg, Fe, Na and S are assigned to minor elements in the ESp (Fig. 2a).

3.3. Tensile properties of eggshell nanoparticles reinforced recycled low-density polyethylene

A progressive increase in the tensile strength up to 10 wt% at which tensile strength attains a peak value is noticed (Fig. 3a). Above 10 wt% of ESp addition, there is a fall in the value of tensile strength though the tensile strength at 12 wt% is still greater than that of the pristine RLDPE. The increase is associated with high structural integrity established with the composite in Fig. 2. Individual ESp connected with the RLDPE matrix serve as the load bearers. When the composite sample was under load, there was an effective load transfer by the RLDPE matrix to the individual ESp which collectively bore the burden of external load constraint. Since the structure is continuous and free from material imperfection, there is no room for any stress localization which may initiate local deformation of the composite under a low stress. Additional stress is needed until the resistance of the reinforcing particles to deformation is overcome. During tension/pull, tiny pores/crazes created due to increasing stress were gradually stretched and fused into one another forming cavities of different sizes. At every step of deformation, there was an increase in the applied stress due to crack/cavity impingements at the approach of stiff/rigid phases within the RLDPE. This progresses till necking occurred due to formation of a big crack from many tiny pores coalesced together. Just before necking, the RLDPE/ESp attained ultimate tensile strength. After necking, there was no further resistance to deformation leading to a decrease in the applied stress until fracture of the composite took place. With an increase in wt% of ESp, there are higher number of individual particles within the matrix corresponding to higher resistance to deformation before an occurrence of the composite necking. This explains an increment in the tensile strength due to ESp addition in Fig. 3a. Smaller value of tensile strength at 12 wt% is linked with defects/imperfections inherent with the composite which interfere with the composite pull during the analysis. Improvement in the tensile strength agrees with literature (Brahmakumar et al., 2005).

3.4. Flexural properties of eggshell nanoparticles reinforced recycled low-density polyethylene

An increase up to 12 wt% in flexural strength is seen in Fig. 3c. A decrease in flexural strength though very slight is noticed at 6 and 8 wt% ESp addition (Fig. 3c). Improvement in flexural strength is linked with stiffening tendencies of eggshell nanoparticles. Each of eggshell nanoparticle firmly bonded to the RLDPE matrix forms a formidable barrier in addition to that of RLDPE grains that delays/blocks craze advancement during the flexural loading. This requires additional stress for craze movement justifying greater flexural strengths of the RLDPE composites than that of the pristine RLDPE polymer. Moreover, number of barriers created by the ESp is a function of their weight fraction i.e number of barriers to crack advancement at 4 wt% is expected to be higher than those at 2 wt% of ESP addition; those at 12 wt% is expected to greatest than those at smaller wt%, which explains the increase in the flexural strength up to 12 wt%. However, the slight decrease at 6 and 8 wt% could be linked with defects that cause discontinuity in the composites and reduce degree of ESp networking within the matrix. The defects assisted the craze advancement via stress raising effects and led to composite's deformation at lower stress than the expectation (Bello and Kolawole, 2020).

3.5. Impact energy and hardness of eggshell nanoparticles reinforced recycled low-density polyethylene

A decrease in impact energy above 6 wt% was a sacrifice for an increase in the hardness values since harder materials absorbs less impact. Moreover, it is established that ESp addition to RLDPE increases impact energy up to 6 wt% whereas the composite maintains hardness value of the pristine RLDPE till 6 wt% above which the improvement in composite hardness is discernible. Generally, improvement in mechanical properties due to ESp addition confirmed in this study is in line with findings from similar research (Mulinari et al., 2017). Basically, the increase in impact energy of the RLDPE composite up to 6 wt% could be linked to interaction of the RLDPE and $CaCO_3$ of ESp at small quantity to give rise to a less hard/soft structure which damp the sudden impact of the hammer with the consequent increase in the energy absorption but above 6 wt%, RLDPE-Esp interaction produced hard/less soft structure which broke easily due to sudden impact of the hammer. Therefore, this results in smaller amount of energy absorbed.

3.6. Properties of the recycled and new low-density polyethylene composites

Tensile strength of the pristine VLDPE is 6.56 ± 0.33 Nmm^{-2} while that of RLDPE is 6.31 ± 0.2 which is 4% smaller than that of the VLDPE. This implies that the RLDPE is comparable with the VLDPE. Upon this, RLDPE can be a substitute for VLDPE in many applications, thereby reducing dependence on VLDPE. This will not only cut the cost of production down as RLDPE is much cheaper than VLDPE but also lowers environmental hazards from exploitation of petroleum of which the olefins, like polyethylene are produced. Furthermore, 6.56 ± 0.33 Nmm^{-2} was established for TASNEE VLDPE used in this research, 9.2 Nmm^{-2} (MPa) was reported for Indothene 16MA400 VLDPE in (Brahmakumar et al., 2005) with an improvement in its tensile strength due to 10/20 mm long coconut coir additions at 0.25% volume fraction. Similarly, 7.8 Nmm^{-2} were reported on tensile strength of VLDPE in (Mulinari et al., 2017) with 125.6, 214 and 64.33% increase in tensile strength, flexural strength and impact energy, respectively at 20% Australian King palm fibers additions. At 10 wt% addition, tensile strengths of VLDPE and RLDPE composites are 12.88 and 10.64 Nmm^{-2}, respectively with 21.1% difference which is higher

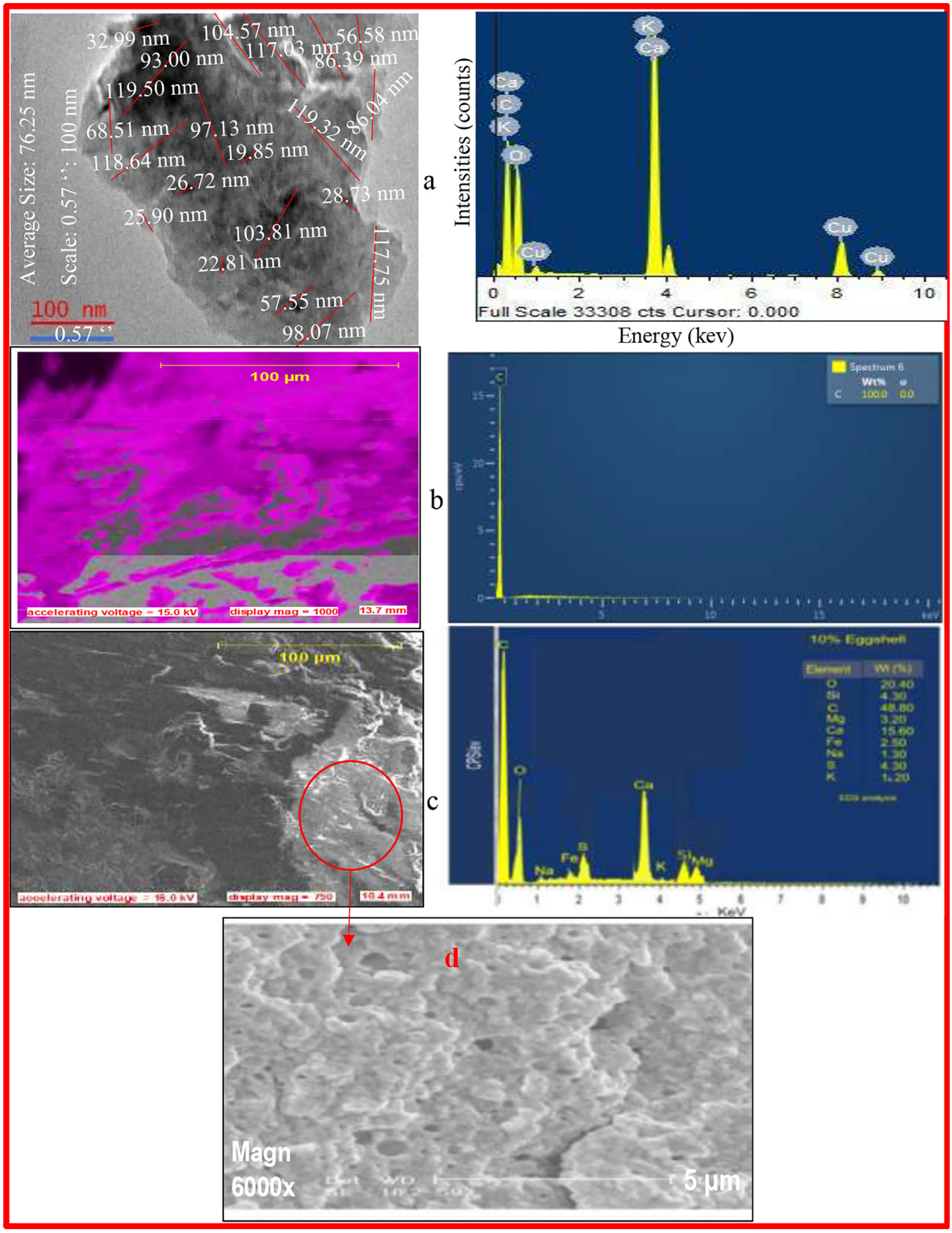


Fig. 2. Microstructures of RLDPE/ESp composites: (a) TEM/EDX of eggshell Nanoparticles (b) SEM/EDX of the pristine RLDPE (c) SEM/EDX of the RLDPE/ESp composite at 1000 magnifications (d) SEM of RLDPE/ESp composite at 6000 magnifications.

than the difference observed with the pristine RLDPE and VLDPE. This implies that ESp addition reinforces the VLDPE than RLDPE. Differences observed in the tensile strength of the VLDPE from a research to another could be attributable to variations in manufacturing techniques and additives incorporated in the VLDPE from a company to another. About 68.4% increase in tensile strength and 36.44% enhancement in flexural strength at 10% ESp addition to RLDPE in this study agree with (Brahmakumar et al., 2005;

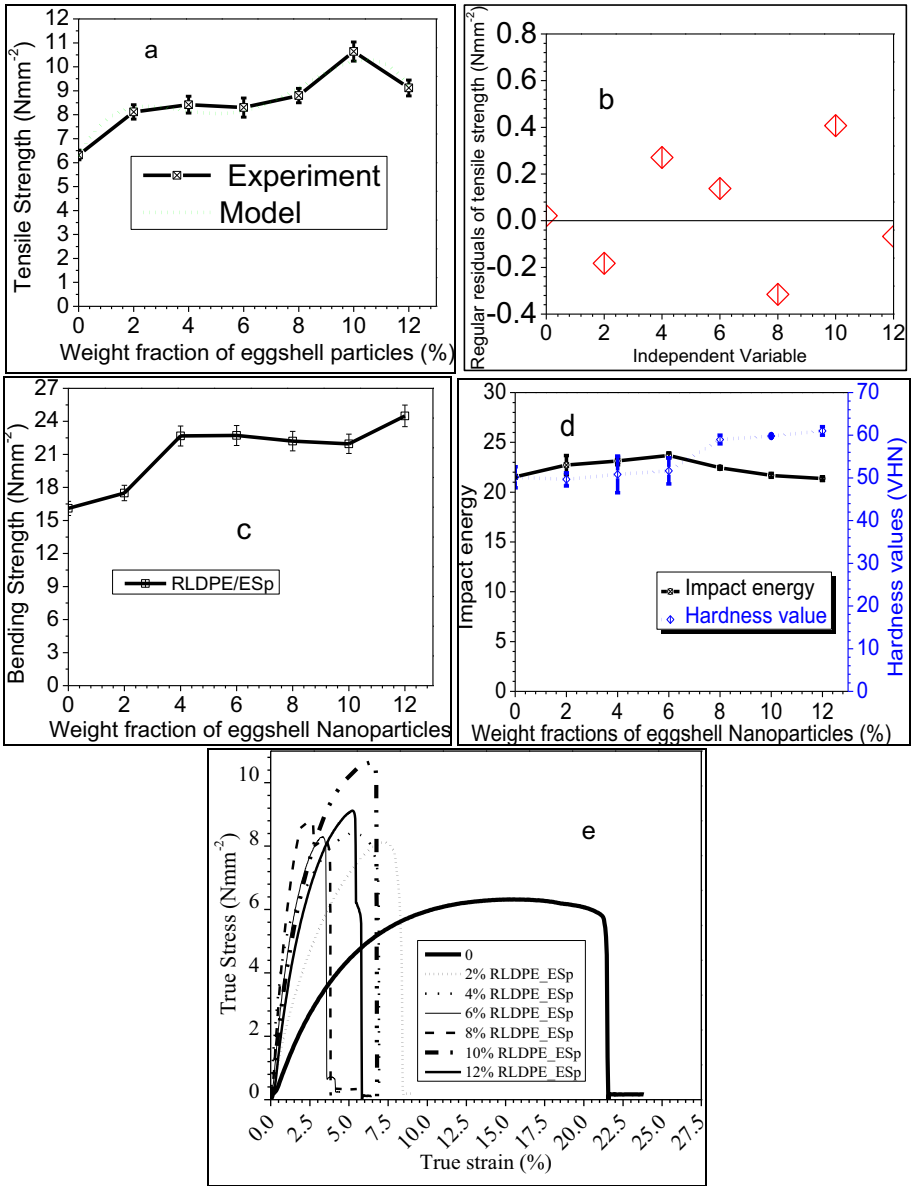


Fig. 3. Technical properties of eggshell Nanoparticle reinforced polyethylene: (a) experimental and modelled tensile strength (b) residual of the tensile strength (c) bending strength (d) impact energy and hardness values (e) tensile flow curve.

Mulinari et al., 2017). Moreover 19.2% increment in hardness values at 10% ESp addition to RLDPE is in line with (Agunsoye and Aigbodion, 2013). About 0.7% improvement in impact energy established in this study implies that addition of 10%ESp to RLDPE causes little or no change in the impact energy though up to 6 wt% ESp addition, impact energy increase is discernible. Finding on impact energy up to 6%ESp addition agrees with finding in (Mulinari et al., 2017) though VLDPE was used in the study rather than RLDPE in the present study. In addition, this finding did not agree with smaller impact energies of RLDPE/bean pod ash and RLDPE/bagasse composites than that of RLDPE found in Agunsoye and Aigbodion (2013), Atuanya et al. (2014b) despite that RLDPE was used as the matrix in all the studies. The difference could have been attributed to nature of the reinforcements but similar behaviour of bean pod ash and bagasse which are different reinforcements like ESp would not make this possible. However, size of the particle is likely to be linked with the difference in % enhancement since ESp addition to the RLDPE that behaves differently from both bean pod and bagasse ash with respect to impact energy are Nanoparticles whereas both beans pod and bagasse ash are microparticles. Therefore, it is inferred that addition of ESp to the RLDPE in this research enhances the tensile strength, flexural strength and hardness value without sacrificing the impact energy.

3.7. Models

4th degree regression model demonstrates an excellent prediction (Fig. 3a). As seen from Equation 1, the tensile strength (Ts) depends on the constant value (6.2989 Nmm^{-2}), wt^1, wt^2, wt^3 and wt^4. Values of β coefficient β_1, β_2, β_3, and β_4 are 2.1223, −0.7378, 0.0969 and −0.004, respectively and their standardized errors are found in Table 2. Constant, β_1 and β_3 being positive contribute to an increase in RLDPE/ESp tensile strength while β_2 and β_4 being negative reduces the tensile strength. Since wt^1 has maximum β value compared with others, its contribution to estimation of the RLDPE/ESp tensile strength is the most important. Therefore, β_1 predicts strong interfacial adhesion between the RLDPE and ESp. Negative values of β_2 establishes poor interfacial adhesion since

Table 2
Beta values with its standard errors.

Values of β		β	β_1	β_2	β_3	β_4
Tensile strength	Value	6.2989	2.1223	−0.7378	0.0969	−0.0040
	Standard error	0.2557	0.5265	0.2269	0.0311	0.0013
		Total	6	134.9112		

ESp is much higher than the binding capacity of RLDPE or imperfections in the RLDPE/ESp composites leading to stress localization. Since the model was developed at 95% confidence (α = 5%), probability value (Pv), 0.0481 < 0.05 affirms that the model is significant to prediction of the RLDPE/ESp tensile strength. Fishers' value (Fv) 20.0417 being very high implies that there is a very low chance for an error to occur during estimation of the tensile strength. Total degree of freedom 6 implies that not less than 6 matrices were solved in estimating the tensile strength of the RLDPE/ESp composite at any wt%. The statistical regression coefficient of determination (R^2) is 92.7% (Table 3). That is, for a tensile strength at any ESp wt%, this model can confidently account for 92.7% of the experimental value. The remnants (±7.3) account for variation between experimental and predicted data known as residuals (Fig. 3b). This implies that the predicted value can be less or greater than the actual value by a maximum of 7.3%. Since 2, 4, 7, 8, 10 and 12 wt % ESp were used for developing the model, validation of the model using wt% different from the list affirms suitability of the model (See Supplementary Fig. 2) for determining the RLDPE/ESp tensile strength. Therefore, the model is in a good term with the experiment. Moreover, 92.7% of R^2 in this study is in line with 93.18, 96.84 and 99.77% reported in literature (Atuanya et al., 2014a; Agunsoye et al., 2019; Bello et al., 2020).

$$Ts = 6.2989 + 2.1223wt^1 - 0.7378wt^2 + 0.0969wt^3 - 0.0040wt^4 \quad (1)$$

3.8. Future direction of recycled low-density polyethylene eggshell nanocomposites

Bumper is designed to protect vehicle and its passengers in an accident via impact absorption. It consists of three components, fascia, bumper beam and bumper damp. The bumper fascia/cover is installed for aesthetics and aerodynamic force reduction. Since the bumper cover is the part that touches an obstacle first in any collision, it is supported by bumper beam via absorption of kinetic energy without transferring it to the rest of the vehicle while the bumper damp/foam absorbs portion of the kinetic energy and prevents or reduces the vehicle vibration during collision. Bumper beam is made from steel over years. It is now being replaced with lighter materials to enhance performance of bumper system and fuel efficiency since plastics absorbs more energy and is lighter than steel. Uses of lightweight materials like plastics for bumper cover is dictated not only by legislations (Fredriksson, 2011; Roger, 2012; Carroll et al., 2014; Fekete and Hall, 2017) to protect the pedestrians in accidental collision with a vehicle in a low speed but also because of their high formability and ease of aesthetics being a soft material. Since the bumper is designed to be impact absorbing, the main material prerequisite for the bumper system is the impact energy in addition to tensile strength. Impact energy, tensile and flexural strength at break of C401-B01 40% chopped fiber mat/polypropylene resin matrix reported by Azdel (one of world material manufacturers) in their datasheet (MatWeb Material Property Data, 2010) for bumper beam are 10–18 J (using ASTM D3763), 105.7 Nmm^{-2} (using ISO 527) and 146 Nmm^{-2} (using ISO 178), respectively. This study establishes a maximum tensile strength of 10.64 Nmm^{-2} at 10%ESp addition to the RLDPE. Impact energy and flexural strength of the RLDPE/10%ESp are 21.69 J and 21.964 Nmm^{-2}, respectively. RLDPE/10%ESp is inferior to the Azdel GMT per tensile and flexural strengths though its impact energy is greater. Therefore, RLDPE/10%ESp may not be suitable technically for fabricating the bumper beam. However, the bumper fascia is ranked a nonstructural member (Belingardi et al., 2017) of the bumper system because of low strength requirement for aerodynamic forces and aesthetics. Although use of polypropylene, polycarbonate and polyurethane are found in literature for fabricating the bumper fascia, recent study disclosed in (Bello et al., 2020) shows an impact energy, tensile and flexural strengths of 21.18 J, 12.23 Nmm^{-2} and 135.16 Nmm^{-2}, respectively for Toyota Sienna (XLE 2010 model) bumper cover and those for Nissan Almera (2010 model) bumper fascia are 25.54 J, 6.44 Nmm^{-2} and 58.30 Nmm^{-2}. Impact energy of RLDPE/10%ESp, 21.69 J is greater than that of the Toyota Sienna bumper fascia but lower than that of the Nissan Almera bumper cover. Its tensile strength of 10.64 Nmm^{-2} is much greater than 6.44 Nmm^{-2} of the Nissan Almera but is slightly smaller than 12.23 Nmm^{-2} of Toyota Sienna bumper fascia and its flexural strength is lower than 135.16 Nmm^{-2} of the Toyota Sienna bumper fascia and 58.3 Nmm^{-2} of the Nissan Almera. Since RLDPE/10%ESp meets up with both tensile strength and impact energy requirements which are the main prerequisites for the fascia, it is inferred that RLDPE/10ESp nanocomposite is appropriate for fabricating the bumper fascia/cover. Moreover, technical requirements play a major role in selecting a material for an application. Ability of the material to be shaped into an appropriate form to be put into the application is also very paramount. Success recorded with ease in fabricating RLDPE/10%ESp bumper prototype using hot press setting to temperature of 100℃ and a pressure of 2–3 N/mm^{-2} is another testimony confirming the suitability of the RLDPE/10%ESp as a candidate material for fabricating the automobile bumper fascia.

Fabrication was achieved via sheet forming process using aluminium alloy mould. RLDPE/10%ESp was processed at 150℃ using two-roll polymer mill to produce rectangular composite blend which was placed in the lower part of the preheated mould already coated with oil acting as lubricant. Upper mould part was set on top of the lower mould via the insertion pin for proper alignment. The mould parts were slowly moved against another with

Table 3
ANOVA of recycled low-density polyethylene-eggshell particle composites.

	Parameters	DF	Sos	Ms	Fv	Pv	S
Tensile strength	Model	4	131.6273	32.9068	20.0417	0.0481	
	Error	2	3.2838	1.6419			
	Total	6	134.9112				
	R-Square						92.7%

DF-Degree of freedom; Sos - Sum of squares; Ms – Mean square; Fv - Fishers' value; Pv -Probability value; S – Statistics.

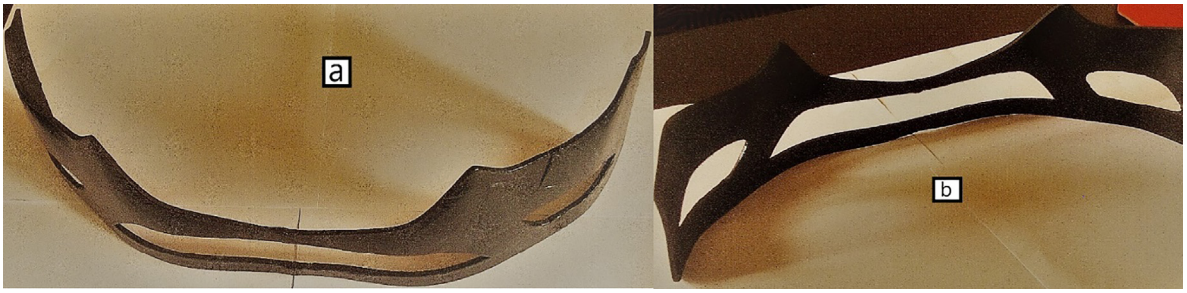


Fig. 4. Recycled low-density polyethylene/10%eggshell particulate nanocomposites (a) front view (b) back view.

RLDPE/10ESp plate being forced into the mould cavity until the flash formation occurs indicating the complete filling of the mould parts. The mould parts were disengaged, the bumper prototype was gently removed from the mould and the bumper after flash removal is displayed in Fig. 4. Therefore, a new artefact was produced from two different wastes, establishing a novel approach to wealth creation from wastes.

4. Summary and conclusions

Eggshell Nanoparticles were produced via combined manual crushing, disc grinding and ball milling. Broader XRD peaks of the RLDPE composites signify straining that affirms an improvement in the load bearing capacity of the RLDPE due to ESp additions. Structural integrity/good interfacial adhesion between the matrix and the particulate reinforcement was affirmed by the SEM. A maximum tensile strength of 10.64 Nmm^{-2} was established at 10 wt% ESp additions to the RLDPE. Incorporation of ESp in RLDPE improves the tensile strength with a consequent reduction in percentage elongation (Fig. 3e). Flexural strength and hardness values were improved up to 12 wt% of ESp additions. Enhancement in impact energy was established up to 6 wt% ESp. Above 6 wt% ESp, falls in composites' impact energies prevails with about 0.85% reduction at 12 wt% compared with the impact energy of the pristine RLDPE. Eggshell Nanoparticle reinforced RLDPE maintains its impact energy despite the increase in the hardness values with an increment in the ESp additions. Validation of the mono-variate regression model at wt% ESp not included in the experimental data for developing the model confirms appropriateness of the model for estimating the composite's tensile strength.

Declaration of Competing Interest

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

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