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RESEARCH ARTICLE

ASSESSING SOUND-MUFFLING CHARACTERISTICS OF FLY-ASH NANO-PARTICLE REINFORCED EPOXY RESIN COMPOSITES

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ABSTRACT

Effective reduction and control of noise have continued to attract attention globally due to the adverse effects noise poses to human health, effective knowledge dissemination and desirable environmental tranquility. The use of natural and synthetic reinforced composites in noise pollution control is an emerging area of research. In this study, coal fly-ash in nanoparticles varied at 5 – 25 wt. % was employed as reinforcement in the fabrication of epoxy resin composites. The composites were characterized both for noise reduction capability and mechanical properties necessary for a damage-free handling during installation. Results showed that samples of the composites at 15 wt. % exhibited the highest noise reduction coefficient (NRC) of 0.8072. This translates to 81% noise reduction capability if deployed in a facility and compares very well with that of conventional acoustical materials that are used in buildings and other facilities. The mechanical properties exhibited by the composite samples in terms of flexural strength (20.3 – 43.7 MPa), impact energy (4.4 – 4.8 J), and hardness (13.3 – 15.3 HV) are sufficient for the intended area of application. Thus, the composite developed at 15 wt. % fly-ash addition is recommended for deployment in auditorium (lecture theatre), public library, hospital ward and hotels. These facilities have maximum recommended noise levels in the range of 35 – 45 db. The composites are adjudged suitable for application as noise muffling materials in buildings and other facilities that are usually subjected to low mechanical system noise sources.

Keywords: Noise pollution, Noise reduction coefficient, Polymer matrix composite, Fly-ash nanoparticles, Mechanical properties

1. INTRODUCTION

Noise being an unwanted sound is a serious social malaise that plague every segment of societies worldwide. It is established that normal sound frequency range for human hearing is 20 Hz – 20 kHz [1]. However, on daily basis people are subjected to noise frequency range between 50 Hz and 50 kHz corresponding to a rather uncomfortable noise level greater than 80 decibels. This underscores the continuous quality attention being placed on how best to reduce significantly the generation and transmission of unwanted sound [2]. Effective noise reduction and control lie in understanding the mechanism by which noise is transmitted. According to [3], the science of hearing sound in spaces can be broadly divided into three stages namely; sound production, sound reproduction and noise control.

Noise control has become an important part of architectural design due to its high probability to harm human well-being causing disruption of normal sleep pattern, hearing impairment, loss of concentration and other debilitating effects. Recent discoveries established that constant exposure to noises can cause both auditory and non-auditory health problems such as cardio-vascular diseases, sleep disturbance and annoyance [4, 5]. Thus, the main goal of most architectural design modification of buildings and structures is to reduce or eliminate the noise power, either outdoors or indoors [6]. Furthermore, the understanding of the nature of sound as a wave which propagates through physical mediums such as air is imperative for effective curtailment [7]. Eventual propagation of sound involves three contiguous processes namely; transmission, absorption and reflection. However, the amount of energy going into transmission, absorption or reflection depends on the surface's acoustic properties. Thus, the sound that is heard is usually a combination of direct sound straight from the source and indirect reflections from surfaces and other objects in the environments. Hence, sound can be controlled either from the source (active control) or from the surroundings (passive control). In real life situations both passive and active sound control is essential in order to perceive the right sound.

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Currently, the common in-door sound muffling materials in use are polymers and ceramics. However, polymers such as vinyl ester, epoxy, and polyurethane in which pores have been induced during processing are most preferred [8, 9]. Epoxy resins are thermosets often used in polymer matrix composites due to their good resistance to chemical attack, lightweight and excellent insulating properties [10]. In order to prevent polymer matrix composites from mechanical damage, they are usually reinforced by either organic or inorganic fillers such as certain industrial wastes including coal fly-ash, carbon black, or processed agricultural waste such as rice husk-ash [11, 12]. Fly-ash is a coal combustion byproduct constituting a major environment problem. It consists of silt-sized spherical particles oxides of silicon, aluminum, calcium, magnesium and other metallic oxides in trace amounts [13]. The unique spherical shape and particle distribution of fly-ash makes it a good filler material in polymer matrix composites. According to [14], the average coal fly-ash annual production worldwide is put at 700 million tons.

In view of the foregoing, the development and deployment of sound absorber materials appear to be the panacea to the pervasive noise pollution in our environments [15, 16]. The aim of this study is to develop and characterize fly-ash nanoparticles reinforced polymer composites suitable for noise reduction purposes.

2. MATERIALS AND METHODS

2.1. Materials and Equipment

The major materials used in this study include epoxy resin/hardener sourced commercially and coal fly-ash obtained from Lafarge Cement Manufacturing Company, Ewekoro, Ogun state, Nigeria. The equipment used for both the composites synthesis and characterization include a ball-mill, mechanical stirrer, FTIR and XRF analyzers to validate the type of epoxy resin used and the fly-ash composition respectively. An impedance tube was used to generate noise parameters data from which the Noise Reduction Coefficients (NRC) of the composites were computed. The mechanical characterization of the composites was carried out using Instron mechanical tester, Avery impact tester and Vickers hardness tester while an optical microscope was used for the microstructural examination.

2.2. Composites Production

Powder metallurgy technique was employed in the production of the composites. The coal fly-ash was milled using a steel ball mill (model A50 43, Mashine, France) and sieved to nanoparticle size using British standardized sieves (BSS). This procedure agrees with the method adopted by [17, 18] concerning ball milling of carbonised organic particles. Sustainability of the procedure is ensured by producing the nanosized fly-ash particles in bulk prior to the commencement of the composite production. Thereafter, fly-ash nano particles production continues simultaneously with the composite production. Then mechanical mixing of the reinforcement with the epoxy resin was carried out according to calculated materials formulation shown in Table 1. Each formulation of the composite weighs 60g and the mixture was stirred vigorously to achieve homogeneous blend and as well exclude air bubbles. The mixture was then poured into prepared wooden molds coated with paper tape which served as the mold releasing agent. This was followed by casting of the composites which were allowed to cure at room temperature for 24 hours and then stripped for characterizations.

Table 1. Materials formulation

Sample	**Matrix**				**Reinforcement**	
	Epoxy resin (g)	Epoxy resin, wt. %	Hardener (g)	Hardener wt. %	Fly-ash nanoparticles (g)	Fly-ash nanoparticles, wt. %
A	40	67	20	33	0	0
B	38	63	19	32	3	5
C	36	60	18	30	6	10
D	34	57	17	28	12	15
E	32	53	16	27	15	20
F	30	50	15	25	18	25

2.3. Sound Absorption Test

The sound absorption tests were carried out in department of Physics laboratory, University of Jos, Nigeria using the Transfer Function Method (TFM). This test method makes use of an Impedance tube configured with a digital frequency analyzer for the determination of sound absorption coefficient as shown in Figures 1 and 2.

Figure 1. Impedance tube

Figure 2. Frequency analyser

The experimental procedure involves five (5) successive steps namely: (i) test sample was fitted to the sample holder and into the impedance while the signal generator was adjusted to give a frequency of 1000 Hz sound wave. Furthermore, the Cathode Ray Oscilloscope (CRO) was adjusted to show the function generator output; (ii) the signal generator output was moved to leave the CRO screen to clear the way for the microphone signal; (iii) the microphone was moved along the axis of the impedance tube until the amplitude of the trace on the CRO is at a minimum while the peak to peak height of the trace was recorded as V_2; (iv) the microphone was further moved until the amplitude of the trace was at a maximum and the peak to peak values recorded as V_1 and (v) the frequency was changed to 2 KHz, 3 KHz, 4 KHz, 5 KHz and 6 KHz respectively while procedures i-iv were repeated for each frequency.

2.4. Mechanical Test

Three-point flexural test was conducted on the composite samples of dimension 12 x 5 x 0.5 cm at room temperature using an Instron electromechanical testing machine according to ASTM D7264 standard. The experiment was conducted under a crosshead speed of 30 mm/min maintained at a span of 100 mm. An Avery impact testing machine was used to evaluate the impact toughness of the samples dimensioned to 5 x 1.5 x 0.5 cm in accordance with ASTM E23 standard. The Vickers hardness values of the composite samples of dimension 4.4 x 4.4 x 0.5 cm were obtained using a micro-hardness tester.

3. RESULTS AND DISCUSSION

3.1. Chemical Composition

The XRF analysis results carried out on the fly-ash nanoparticles (FLA_{NP}) is presented in Table 2.

Table 2. Composition of fly-ash

Composition	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**K_2O**	**CaO**	**MgO**	**P_2O_5**	**TiO_2**	**Na_2O**	**SO_3**	***L.O.I**
Wt. %	50.23	25.85	6.31	3.84	3.22	2.00	1.39	1.17	1.20	0.09	4.70

*Loss on Ignition

The result in Table 2 shows that fly-ash consist of relatively high silicate glass known as cenospheres followed by Al_2O_3, Fe_2O_3, K_2O, CaO, MgO, P_2O_5, TiO_2, Na_2O, SO_3. According to [13], cenospheres consist of silicate glass in which the silica content is higher than the calcium content. The main application of cenospheres is as inert fillers, in which they often provide up to four times the bulk filler capacity. Furthermore, being inert, they are resistant to most acids and high temperature conditions. Thus, cenospheres can be used in plastics, glass-reinforced plastics, light-weight panels, refractory tiles and almost anywhere that traditional fillers can be used [19].

3.2. Fourier Transform Infrared (FTIR) Spectroscopy

The FTIR result presentes in Figure 3 shows that the epoxy rein used is Diglycidyl ether of bisphenol-A (DGEBA). Although, the spectra look similar to its hydrogenated derivative (HDGEBA), but the differences become obvious from the difference in peak values coupled with the absence of aromatic rings in HDGEBA. These features usually influence epoxy resin functional properties such as the glass transition temperature, viscosity and reaction rate [20]. The highest peak of the epoxy resin observed at 1510.31cm^{-1} is within the carbonyl region (1500-1700cm^{-1}). This is common for epoxy resin as they show prominent C=O peaks in this region. These days the use of epoxy resin in natural fiber based composites is gaining prominence owing to its low weight, ease of synthesis and competitive cost. Furthermore, epoxy in natural fiber based composites have been found to confer excellent sound attenuation characteristics coupled with environmental friendliness and minimal impact on human health [21]. Hence, researchers [22, 23] are proposing its usage as a viable replacement for glass-fiber composites especially in applications where sound absorption is important.

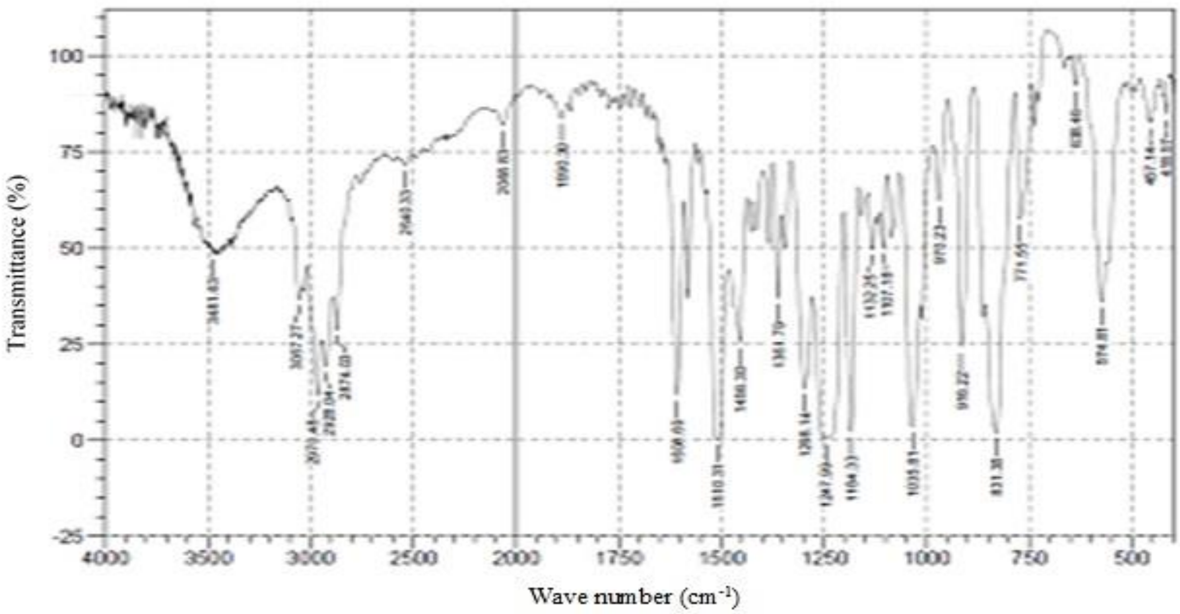

Figure 3. FTIR of the as-received epoxy resin

3.3. Microstructure

The optical micrographs of the composites at varied FLA_{NP} addition are shown in Figure 4b – 4f. Addition of FLA_{NP} influenced the microstructural features to the extent of fractions of pores dispersed homogeneously within the epoxy resin matrix. However, the control sample's micrograph without filler is devoid of pores (Figure 4a). At 5 – 15 wt. % FLA_{NP} addition, varied fractions and sizes of pores are seen dispersed evenly within the matrices (Figure 4b – 4f). The pores in Figure 4b appear isolated while the pores in Figure 4c and Figure 4d developed into a network in a peculiar textural pattern as FLA_{NP} addition increased from 10 wt. % to 15 wt. %. Further increase in FLA_{NP} addition at 20 – 25 wt. %, the matrices (Figures 4e and 4f) appear saturated and the fillers completely subsumed in the epoxy resin. Formation of pores may have stemmed from the combination of vacuum created during cross-linking and condensed moisture due to the hydrophobic nature of epoxy resin. The dynamics of sound impact on a material can be liken to the process of wave generation and propagation. The mechanism by which such wave is absolved and reflected depends on the material structure such that continuity in structure ensures thorough passage of the wave through the material [3, 6]. However, the presence of vacuum within the material favors a situation where significant portion of the wave is absorbed. In this study, the presence of pores developed in the material as shown in the micrographs serve as sound waves sink. The preponderance of inter connected pores in the composites further enhances the attenuation capability of the composites. In particular, Figure 4d shows significant presence of inter connected pores that may enhance its sound absorption ability.

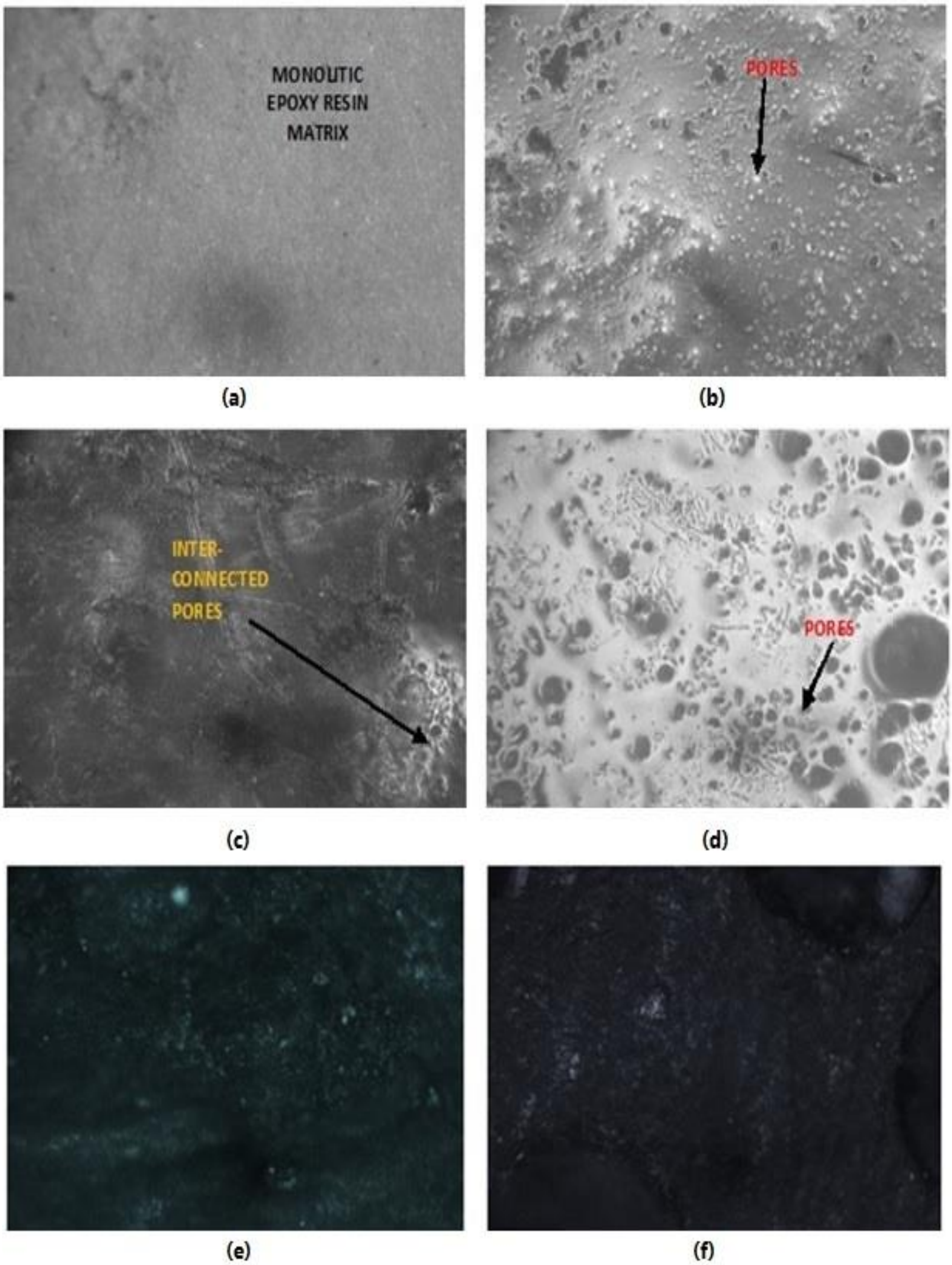

Figure 4. Optical micrographs at varied fly-ash addition (a) 0 wt.% FLA_{NP}, (b) 5 wt.%, FLA_{NP}**, (c)** 10 wt.% FLA_{NP}**, (d)** 15 wt.% FLA_{NP}**, (e)** 25 wt.% FLA_{NP}, (f) 25 wt.% FLA_{NP} x200

3.4. Sound Absorption Response

The sound absorption response of the fly-ash nanoparticles reinforced epoxy resin at varied sound frequencies from 1 – 6 kHz is presented in Table 3.

Table 3. Sound absorption coefficient (SAC)

Frequency (kHz)	SOUND ABSORPTION COEFFICIENT (α)					
	A	B	C	D	E	F
1	0.8889	0.8889	0.5925	0.8594	0.1519	0.1814
2	0.4898	0.2602	0.6567	0.6980	0.1249	0.7601
3	0.8889	0.8741	0.9902	0.5017	0.9722	0.5707
4	0.7500	0.8889	0.8405	0.9711	0.2215	0.4375
5	0.6036	0.8568	0.8741	0.8889	0.3803	0.5556
6	0.6400	0.9467	0.8889	0.8889	0.9902	0.1814

The SAC values in Table 3 indicate the sound absorbing properties of fly-ash reinforced epoxy resin at different frequency. Computation of SAC data for application is rather cumbersome and not easily comprehensible. Hence, for application purposes, Noise Reduction Coefficient (NRC) is usually adopted as expressed in using equation (1) [24].

$$\mathrm{NRC} = \frac{(\alpha 1 + \alpha 2 + \alpha 3 + \alpha 4 + \alpha 5 + \alpha 6)\ \mathrm{kHz}}{6} \quad (1)$$

Where: α_n = Sound absorption coefficients at 1kHz, 2kHz, 3kHz, 4kHz, 5kHz, and 6kHz.
Substituting SAC values in equation (1) for each sample formulation yields the NRC values of 0.7102, 0.7859, 0.8072, 0.4735 and 0.4478 respectively for samples A, B, C, D, E and F.

The sound muffling capacity of the composites as illustrated in Figure 5 correlates the microstructural features in terms of the nature and dispersion of pores formed. NRC measures how well materials stop sound from reflecting (how much sound they can absorb). The NRC is the percentage of sound that a surface absorbs (in other words, hits a surface and does not reflect back again into the room). A material is usually considered to be a sound absorber if it has an NRC value greater than 0.35 [25]. To be an effective sound absorber, a material must have interconnecting air pockets or pores [25].

Hence, pores in this case serve as sound sink where sound in the form of vibration incident on the composites is significantly absorbed releasing just a fraction at low decibels between 35 db and 45 db. The effectiveness of the pores sound muffling capacity is dependent on their interconnectivity [3]. This accounts for the peak performance of samples C and D (10 and 15 wt. % FLA_{NP}) which exhibited the highest NRC value of 0.8072. Materials sound absorption capability depends on acoustic impedance of the media which is a function of the frequency [11]. In this case, frequency approximates different sources of sound including mechanical vibration such as from air-conditioner, washing machine, electric generator all accommodated in a building. From Table 3, it is observed that at a relatively highfrequencies; 4-6 kHz the SACs are in the range of 0.89-0.97. This means that efficiency of the composites is ensured when the sound source synchronizes with the acoustic panel capacity. Sustained elevated sound absorption above 80 decibels is known to be injurious to human health sometimes resulting in hearing damage. However, from the results in Table 3, the optimum mixture containg 15 wt. % fly-ash exhibited such NRC (0.807) that appears sufficient for desirable sound muffling need in facilities such as hospital wards, conference halls, public library, etc. Generally, noise levels in these facilities which are in the range of 70-120 db can be muffled down to as low as 35-45 db by deploying the optimum mixture composite panel. Other acoustic materials that exhibit comparable performances include acoustic tile (0.9), carpet over concrete (0.72), 25 mm fiberglass board (0.98), etc.

The NRC value (0.8072) of sampes C and D compared very well with that of conventional acoustical materials that are used in buildings and other facilities presented in Table 4. Samples C and D must have possessed a relatively high volume fraction of inter connected pores compared to sample A with predominantly isolated pores. The sound muffling ability of the composites at 20 – 25 wt. % fly-ash nanoparticles addition was impaired due to the absence of functional pores as the matrices were completely saturated with the filler.

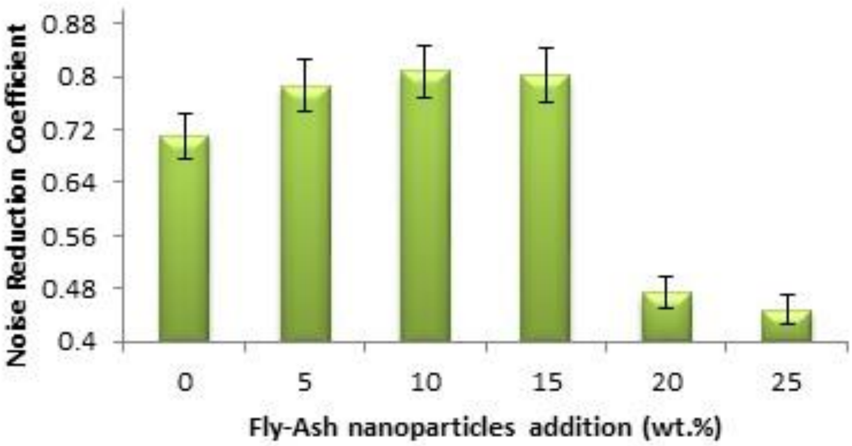

Figure 5. Noise reduction coefficient (NRC) of epoxy resin at varied fly-ash addition

Table 4. Noise reduction coefficient of conventional acoustical materials [25]

Materials	NRC
Brick (unglazed)	0.05
Concrete block (unpainted)	0.05
Carpet (combined pile and foam)	0.35
Fabric (heavy velour)	0.60
Fabric (medium velour)	0.55
Floors (concrete)	0.05
Floors (wood)	0.10
Glass	0.05
Gypsum board	0.05
Marble or glazed tile	0.00
Plaster (gypsum or lime)	0.05
Plywood paneling	0.10
Wood roof decking	0.15
Commercial board (CB) unfaced 150	0.80 – 1.00
Commercial board (CB) unfaced 225	0.70 – 1.05
Commercial board (CB) unfaced 300	0.70 – 1.05
Commercial board (CB) unfaced 600	0.75 – 1.00
Black acousta board (TYPE 225)	0.65 – 0.95
Black acousta board (TYPE 300)	0.70 – 0.95

3.5. Flexural Strength

The flexural property of the composites at varied filler addition is depicted in Figure 6. This is the measure of the composites ability to withstand unrecoverable warpage or fracture under bending load. The control sample (unreinforced epoxy resin) exhibited the highest flexural strength of 56.1 MPa which decreased monotonously as fly-ash nanoparticles increased from 5 – 25 wt. % corresponding to 43.7 – 20.3 MPa. This behavior agrees with [26, 27] which is attributted to bending stiffness often resulting in limited plastic deformation with a tendency for brittle fracture. The pattern of flexural strength performance by the reinforced samples is attributed to the quasi discontinuity in structure occasioned by pore formation. This gave rise to a rather poor load transfer between the reinforcing phase and matrix thereby causing concomitant decrease in flexural strength commensurate to the increase in fly-ash wt. % addition. Considering the report by [28, 29], the range of flexural strength (43.1 – 33.9 MPa) demonstrated by the composite samples at 5 – 15 wt. % fly-ash addition is adjudged sufficient for both damage-free installation and durability in service of the panels.

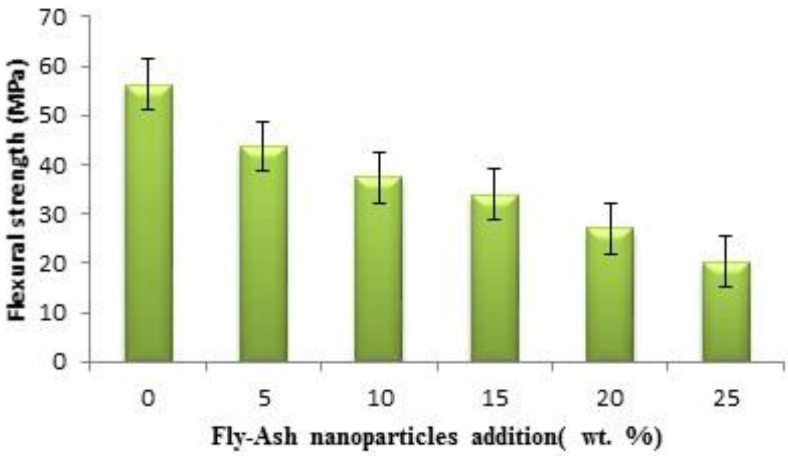

Figure 6. Flexural strength of epoxy resin at varied fly-ash addition

3.6. Impact Energy

The impact energy of the unreinforced epoxy resin is relatively high, 3.6 J but failed to measure up to dynamic stability at varied fly-ash addition as shown in Figure 7. However, the highest impact energy of 4.8 J was exhibited at 5 wt. % fly ash addition. This may be attributted to moisture induced within the matrix during synthesis, epoxy resin being hydrophobic in nature. According to [30], moisture absorption has a deleterious effect on Charpy impact toughness of polymer matrix composites. At 5 – 15 wt. % fly-ash addition, impact energy range from 4.8 – 4.4 J which is adjudged sufficient for the intended area of application. However, the relatively low impact performance of the composites may be attributed to impaired strength of cross-linked chains arising from pores induced discontinuity in the structure.

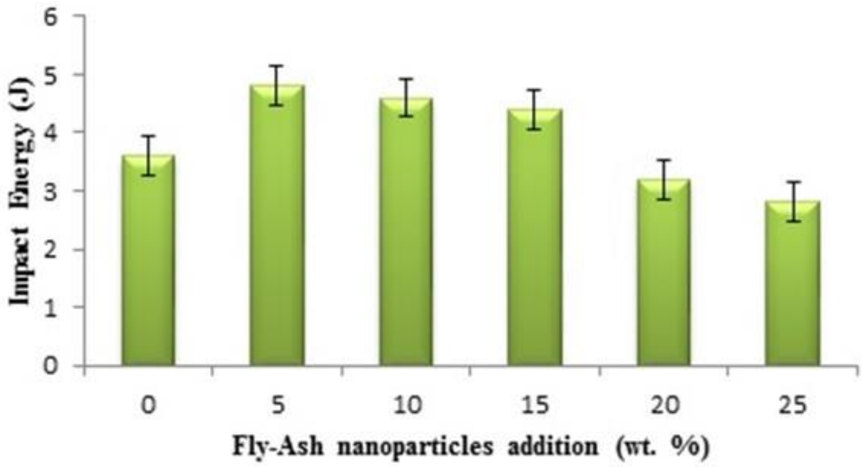

Figure 7. Impact energy of epoxy resin at varied fly-ash addition

3.7. Hardness

The surface resistance to damage demonstrated by the composites was evaluated through Vickers hardness technique and the result is illustrated in Figure 8. Due to the microstructural features induced in the composites on fly-ash nanoparticles addition (Figure 4b – 4f), a modest level of hardness, 25.4 – 19.5 HV was exhibited at 5 – 15 wt. %. However, a highest hardness value of 25.4 HV was exhibited at 5 wt. % fly ash addition. Decrease in hardness in the range of 15.3 – 13.3 HV at 20 – 25 wt. % addition could be due to de-bonding phenomenon between the matrix and the reinforcing phase sequel to the impairment of epoxy resin cross-linking cohesion [31]. The relatively high hardness value (25.4 HV) demonstrated by the 15 wt. % fly-ash nanoparticles mixture was enabled by the intrinsic high hardness of nano particles which provided resistance to the movement of epoxy resin chain on application of load on it. This agrees with [32] as reported in the case of polymer matrix composite reinforced wit nano silica particles and glass fibers.

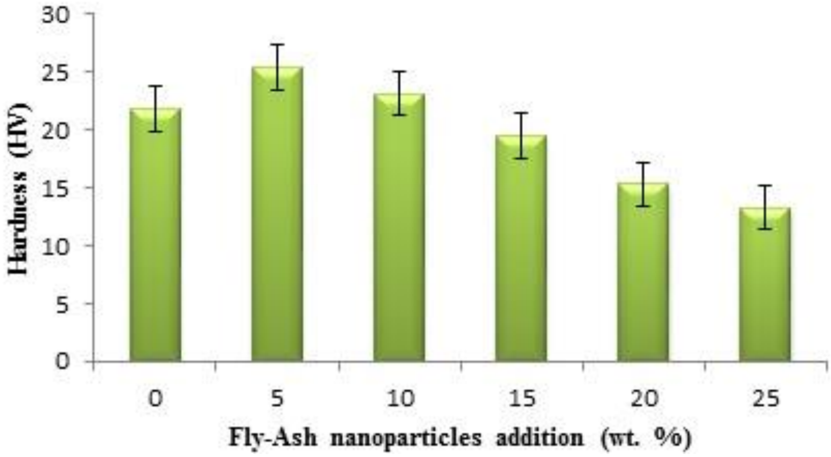

Figure 8. Hardness of epoxy resin at varied fly-ash addition

4. CONCLUSION

Assessment of the noise level abatement capacity of synthesized fly-ash nanoparticles reinforced epoxy resin composites has been successfully carried out. Relevant mechanical properties necessary for damage-free installation were also investigated. The inducement of inter-connected pores in the composites at 10 and 15 wt. % fly-ash addition gave rise to desirable Noise Reduction Coefficient (NRC) value of 0.8072. The NRC value (0.8072) of sampes C and D compared very well with that of conventional acoustical materials that are used in buildings and other facilities presented in Table 4 which may be vulnerable to noise pollution. Samples C and D must have possessed a relatively higher volume fraction of inter connected pores compared to other samples which facılıtated enhanced NRC. The mechanical properties exhibited by the composite samples in terms of flexural strength (20.3 – 43.7 MPa), impact energy (4.4 – 4.8 J), and hardness (13.3 – 15.3 HV) are appreciable and considered to be sufficient for safe handling and durable for the intended areas of application.

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