Long Term Thermo-mechanical Prediction of Banana Stem Particulate Reinforced PVC Composite as Piping Material

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Abstract

A banana particulate reinforced polyvinyl chloride (PVC) composite was developed with low cost materials having an overall light-weight and good mechanical properties. The specimen composite material was produced with the banana (stem) particulate as reinforcement using compression molding. The composition with optimum mechanical property (42MPa) was determined at 8, 72 and 20% formulation of banana stem particulates (reinforcement), PVC (matrix) and Kankara clay (filler) respectively with corresponding density of 1.24g/cm^3 and tensile strength of 42MPa. Thermal analyses of the composited showed that the thermal stability of PVC was increased by 27.8% and is thermally stable up to a temperature of 370ºC. It was established that Long term TTS (time-temperature-superposition) performance prediction increases with decrease in operating temperature with the best determined at lowest considered temperature of 40ºC having a corresponding reduced stiffness of 1GPa at an estimated period in excess of 100 years of usage. The composite could be used as a transportation and distribution piping material for water (to domestic houses) and fuel (to city centers) where ambient temperature does not exceed 50ºC.

Keywords: Particulate composite; TGA/DTA; DMA; TTS; Piping material

1. Introduction

Prediction of long term behavior of material with short term experimental tests has gained considerable attention and importance. Thus time-temperature-superposition (TTS) is a very useful technique in predicting long term performance of polymer based materials by shifting tests curves performed at various temperatures horizontally along logarithmic time scale to generate a curve known as the master curve. The influence of high temperature and long term (time) has similar effect on polymer materials. Materials for which TTS is valid are called thermo-rheologically simple materials [1, 2]. Commonly used superposition principles are the Boltzmann and William-Landel-Ferry (WLF) models. The Boltzmann is given by the Arrhenius equation as [3, 4]:

$$\log a_T = \frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \quad (1)$$

where a_T is the horizontal (time) shift factor, E_a is the activation energy, R is the universal gas constant, T_{ref} is the reference temperature (K) and T is the temperature at which the test is performed.

The WLF is given by the equation as:

$$\log a_T = \frac{C_1(T-T_{ref})}{C_2+(T-T_{ref})} \quad (2)$$

Where a_T is the horizontal (time) shift factor, C_1 and C_2 are constants, T_{ref} is the reference temperature (K) and T is the temperature at which the test is performed.

Tajvidi [5] applied TTS principle on Kenaf-fibre/HDPE composite (50% kenaf fibres, 48% HDPE and 2% compatibilizer) and determined that a single horizontal shift is not adequate to determine the long term performance characteristics of the material. Neielson *et al.* [6] investigated that TTS could be applied to complex thermorhelogically polymer material if the vertical shift factor which is also strongly dependent on temperature is employed. Challa *et al.* [7] investigated the effect of temperature on the creep characteristics of polycarbonate and developed a relationship based on Arrhenius theory to develop creep master curves. Hadid *et al.* [8] estimated four parameters for describing the deformation occurring in the material and used stress–time superposition principle to predict long-term material creep behavior of injection molded fiber glass reinforced polyamide. Master curves were developed and a perfect superposition of the curves at various stress levels was visualized.

Pooler [9] applied TTS on wood-fibre reinforced HDPE and concluded that the material was thermo-rheologically simple and that only a horizontal shifting was adequate to correctly

superimpose the creep data. Dynamic mechanical analysis (DMA) tests were used to determine the shift factors with only the storage modulus curves ignoring other visco-elastic parameters. Dan-asabe *et al.* [10] determined the dynamic mechanical analysis of aluminum reinforced PVC composite as a feasible alternative material for automotive bumper application. Dan-asabe [11] also determined and characterized the thermo-mechanical properties of banana particulate reinforced PVC composite as piping material.

Composite material is the blending of two or more materials to create a new material that is stronger, lighter (less comparable weight) and easier (advantageous) to work with than the individual material such as metal, ceramics and plastic [12]**.** Composite materials are classified based on structural design i.e. type of reinforcing element and its disposition in the matrix; material type i.e. type of matrix and reinforcements and their properties; processing technology i.e. production process [13]. Composite primarily consists of matrix and reinforcement and in addition may contain a third component known as 'filler'. The filler is mixed with the matrix during fabrication and may not necessarily improve the mechanical properties but rather some aspects of desired considerations. Application of composite are found in the automotive, aerospace, marine, architectural structures and some consumer products such as golf clubs, skis and tennis rackets [14]. Research in alternative piping material is very significant as the networks of pipes in the US, Europe and Russia run to about 1,200,000km [15]**.**

The use of conventional steel pipes in the petroleum industries is plagued by high cost of maintenance, corrosion and lower life cycles. The total annual cost of corrosion in the US oil and gas industry is estimated at $ 1.372 billion, with $ 589 million representing pipeline and facility costs, downhole tubing expenses consuming $ 463 million and $ 320 million capital expenditures for corrosion control [16, 17]. Metallic pipe corrosion costs the global world approximately $ 2.5 trillion with the US and China contributing about $ 451.3 and $ 394.9 respectively [18]. Control of corrosion requires expensive prescription to control the onset and its spread overtime. Uncontrolled corrosion could amount to 30% of the total capital expenditure [19]. Use of composite pipe is expected to greatly reduce economic losses as a result of corrosion and high cost of maintenance.

The research work seeks to determine the long term performance prediction of composite of banana particulate as developed by Dan-asabe *et. al.* [20]. Material characterization using DMA (dynamic mechanical analysis) was done to establish its applicability as piping material.

2. Experiment

2.1 Materials

Materials were selected based on availability, weight, corrosion resistance and low cost [11]. Materials used are *Kankara* kaolin clay (200g), Polyvinyl chloride (PVC, 500g), Banana stem (200g), Sodium hydroxide (NaOH), and distilled water (5 litres).

2.2 Material Preparation

The banana stem was cleaned and dried in the sun. The fibres were then manually removed by scrubbing on a rough surface and then cleansed with 1.5M sodium hydroxide in accordance with Kalia *et al.* [21] to enhance the fibre-matrix interface adhesion and later on dried in the sun [22, 23]. The fibres were then ground and sieved with a sieve size of 130µm. The *Kankara* clay was also sieved with same sieve size.

Density of the banana particulate and Kankara kaolin clay (in powdery state) were determined using PVC [24] as the reference with known standard true density of 1.35g/cm^3 in accordance with Dan-asabe *et al.* [25]. These were determined as 0.6 and 1.8g/cm^3 for the banana particulate and kaolin clay respectively. The composition of banana particulate and PVC were varied. The banana particulate was varied from 0%, 8%, 16%, 24%, 32% and 40% for samples 1 – 6 respectively. PVC was varied accordingly from 80%, 72%, 64%, 56%, 48% and 40% respectively. The *Kankara* kaolin was kept constant at 20%. The composition of the constituents was carried out using weight averaging consideration [26] as given in Table 1.

Table 1: Composition of constituents by weight

Samples	Compositions (g)		
	Banana particulate	PVC	Kankara Clay
Sample 1	0	44.0	11.0
Sample 2	4.4	39.6	11.0
Sample 3	8.8	35.2	11.0
Sample 4	13.2	30.8	11.0
Sample 5	17.6	26.4	11.0
Sample 6	22.0	22.0	11.0

2.3 Mold Design

The Initial design parameters include the yield strength of the mold (structural) steel, σ_y taken as 250 MPa, constant compression pressure (P) of 20.7 MPa applied on the mold, dimension of the rectangular mold taken as 124 × 40 mm (a × b) and factor of safety, S_f taken 1.7 [27]. The maximum bending equation at edge of the plate, M_{be} was considered as it provides a greater minimum thickness than at the center, M_{bc}. The rectangular thick plate was assumed fixed at both ends [28]. The minimum thickness was determined using the following equations [28, 29];

Maximum bending moment per unit width;

$$M_{be} = \frac{P\,b^2}{12(1+(b/a)^4)} \quad (3)$$

$$= \frac{20.7 \times 40^2}{12(1+(124/40)^4)} = 2730.23N$$

Allowable (working) stress generated;

$$\sigma_{all} = \frac{\sigma_y}{S_f} = \frac{6M_{be}}{t^2} \quad (4)$$

Therefore, minimum plate thickness;

$$t = \sqrt{S_f \frac{6M_{be}}{\sigma_y}} = \sqrt{1.7\frac{6 \times 2730.23}{250}} = 10.55\text{mm}$$

Hence, 11 mm was taken as the thickness of female and male mold.

The shape of the mould was fabricated in such a way that after hot compression the composite will be reduced to half its initial volume to ensure excellent compaction (devoid of pores between the constituents) as shown in Fig. 1. Material used for the mold is medium carbon steel. The size of the groove for the female component is 100x40x10 mm. The size of the male protrusion part is 99x39x5 mm. Each sample was put into the female mold to fill it and the excess put off.

2.4 Compression molding process

This was carried out with Carver-3851 compression machine. Each sample was pressed at a temperature of 250ºC and a compression pressure of 20.7 MPa for 20 minutes [30]. This temperature was used because preliminary trials with temperatures above it produced burnt product and temperatures below it produced less compacted product. The compression pressure (20.7 MPa) was the maximum pressure reached for the first test sample (reducing mold volume by half) and was adhered to for the remaining samples. Samples obtained were cooled and machined in preparation for mechanical, microscopic and spectroscopic tests.

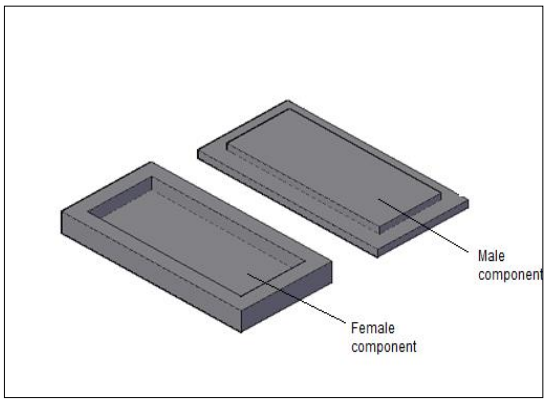

Fig. 1: Composite male and female part of the mold

3. Characterization

3.1 Density and Tensile Strength

The density of the composites was determined by measuring its respective mass and volume. Sample specimens of dimensions 20x20x5 mm were produced for the test. The mass was determined with the aid of a computerized weight balance machine to an accuracy of four decimal places. The volume of each sample was found using Archimedes's principle.

The tensile strength was determined using an Electronic Tensometer ER–3 according to ASTM E8 standard [31]. Sample specimen dimensions of 120x8x5 mm with dumb bell shape outside the gauge length were produced for the test. The dumb bell part was clamped to jaws of the machine and the extension was produced within the gauge span of the specimen. The tensile strength was calculated as maximum force per unit cross-sectional area in the following equation:

$$\sigma = \frac{F}{A} \text{ (MPa)} \quad (5)$$

where F = force, e = extension, l =original length and A = cross-sectional area.

3.2 TGA

Perkin Elmer thermal analyzer was used to conduct thermogravimetric analysis on the sample composite. At the start of the experiment, the purge gas (nitrogen) was continuously passed into the furnace at a flow rate of 20ml/min to condition

the furnace. Sample quantity of approximately 1 gram was placed evenly distributed in an open pan of 6.4mm diameter by 3.2mm depth. The temperature was controlled from ambient to 830ºC at a heating rate of 10ºC/min and cooling at 20ºC/min [32]. The test was carried out in FUT Minna Step-B new research centre.

3.3 TTS

DMA (dynamic mechanical analysis) and TTS (time-temperature-superposition) were simultaneously carried out using DMA 242E machine [33] in strength of materials laboratory of mechanical engineering, A.B.U. Zaria. The test parameters were first configured via the Proteus software using the computer (PC). Parameters such as evaluation functions (storage modulus, tan d and deflection), instruments set up (sample holder, furnace temperature and furnace thermocouple) and measurement mode (temperature, static and dynamic loads) were configured. Sample specimen of dimension of 60x12x5 mm was produced for each test. The sample was loaded on to the machine using three-point-bending sample holder and subsequently locked into the furnace. The test was then carried out for the respective DMA and TTS (Time-temperature-superposition).

4. Results

4.1 Physico-mechanical (Density, Tensile Strength and SEM)

Graphical depiction of the density with increasing weight fraction of the particulate (reinforcement) indicated decrease in density of the composite (Fig. 2). The Fig. 2 also shows the ultimate tensile strength (UTS) of the composite with increasing weight fraction of the particulates. However the tensile strength increases and then decreases steeply. It is interesting to note that maximum is achieved at 8% weight fraction of the reinforcement. The result was compared with a doum palm fibre reinforced propylene composite as developed by Essabir *et al.* [22]. The tensile strength at 10% weight of fibre with and without coupling agent were determined as 29MPa and 26MPa respectively are less than those of the composite of banana particulates at 10% reinforcement.

Scanning electron microscopy (SEM) microstructure of the composite at 8 % reinforcement is shown in Fig. 3 depicting a fairly uniform distribution of the constituent materials at 1000×. The continuous flow (grey colour) vividly indicated the polymer (PVC) as the matrix, the non-glossy particles indicated the banana particulate as the reinforcement and the glossy semi-crystalline particle (white colour) indicated the Kankara clay as the filler.

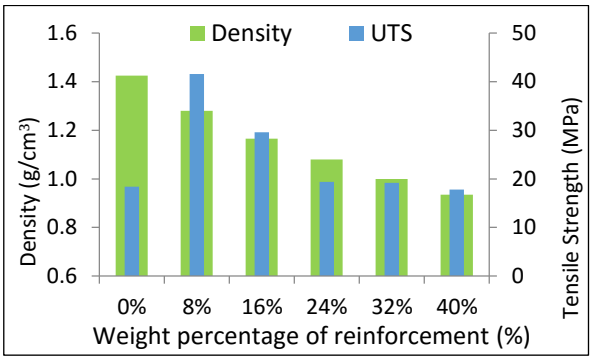

Fig. 2: Effect of density and water absorption on weight fraction of reinforcement

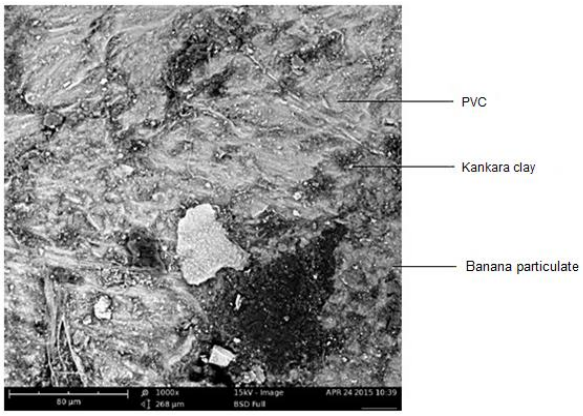

Fig. 3: Microstructure of composite ×1000

4.2 Thermo-mechanical Analysis

4.2.1 TGA/DTA

The result of thermal test (DTA and TGA) for composite is shown in Fig. 4. The faint curve (blue) represents the DTA while the darker curve represents the TGA of the composite. The TGA measures the change in weight of the sample in relation to change in the controlled temperature. The curves showed the thermal scan between 29ºC to 830ºC. The onset temperature of decomposition (TGA) of the composite started at approximately 370ºC and continuously up to 530ºC with a corresponding mass depletion of 47%. The second stage of decomposition is 530ºC – 670ºC with a mass depletion of 23%. The total mass depletion from the thermal treatment is approximately 70%. The mass depletion is as a result of full decomposition of PVC and evaporation of some oxides of the kaolin clay and natural particulate substance (doum palm).

Decomposition of PVC is a two-step process involving dehydrochlorination by releasing HCl and the formation of conjugated polyene sequences. The second step is the decomposition of polyene back ones and formation of residual chars [34]. The DTA curve showed percentage mass decomposition rate for the two respective stages of 370ºC – 550ºC and 550ºC – 670ºC mass depletion. This was attributed to first and second stage decomposition of PVC and oxidation of some impurities of the banana and kaolin clay. Similarly, Fig. 5 depicts TGA/DTA curve of pure PVC with its mass decomposition stages of 267ºC – 390ºC and 390ºC – 510ºC respectively [35]. The curve showed a total mass depletion of 95% leaving only remains of the residual chars (5%). Comparison of Figures showed that the composite increased the thermal stability of the PVC by 103 ºC. The TGA/DTA curves simultaneously showed that the composite is thermally stable up to a temperature of 370 ºC.

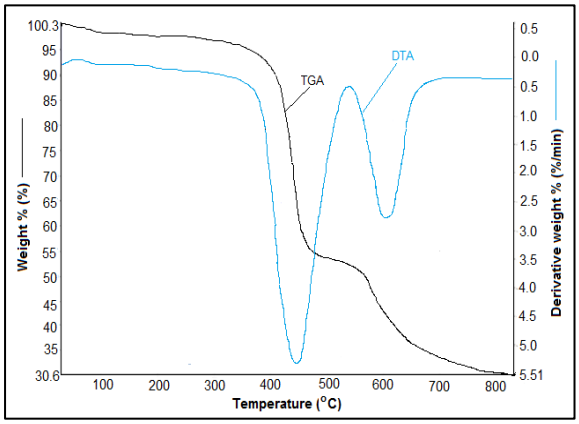

Fig. 4: TGA/DTA curve of composite of banana particulates

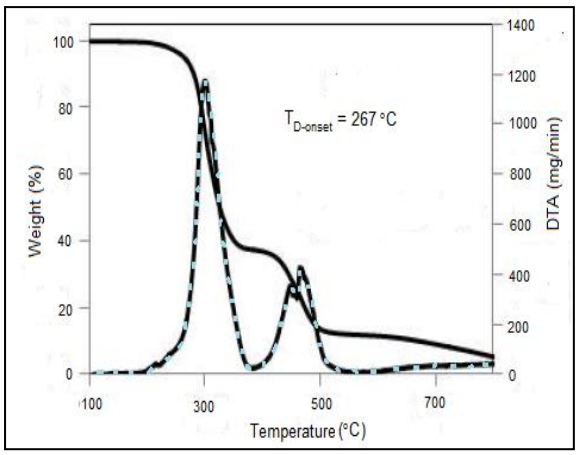

Fig. 5: TGA/DTA curve of pure PVC [35]

4.2.2 DMA

DMA The dynamic mechanical analysis (DMA) depicts the stiffness stability of the composite with increasing temperature, its glass transition temperature and its visco-elastic nature when stimulated by dynamic loading. The DMA curve of the composite is depicted in Fig. 6. The test was carried out under a load stress of 150KN/m^2 slightly above atmospheric pressure. This is because atmospheric pressure is the only load stress that acts on an unburied pipe under normal operating condition (neglecting other rare unexpected conditions e.g. snow, drought, earthquake etc.). The curve shows the composite is stable under dynamic loading (having zero strain) with increasing temperature at frequencies of 1, 5 and 10Hz up to 70°C before the onset glass transition temperature of 74.5°C (with corresponding point of inflexion of 79.3°C). The onset glass transition temperature of PVC pipe is 65.8°C and its point of inflection (mid-point) usually taken as the glass transition temperature is 66.9°C [11, 36]. The curve also showed about 22% loss of stiffness from 1.2GPa to 0.9GPa at 70°C. This indicates the suitability of the use of the material up to 70°C. The *tan d* (tan delta) value is the ratio of the viscous to elastic modulus and thus gives a measure of the visco-elasticity of the material. The visco-elasticity of composite of the banana particulate is eminent at *tan d* value of 0.1 from 70°C up to a maximum of 1 at 97°C.

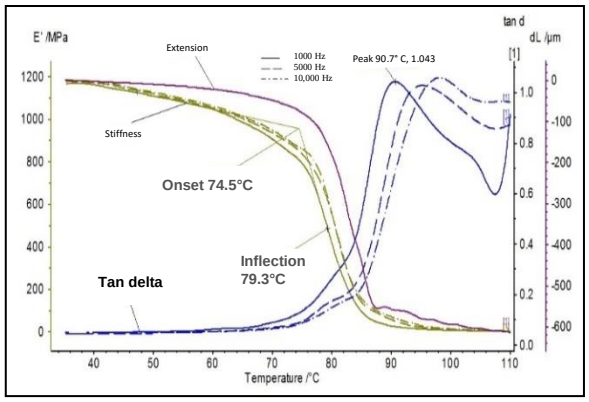

Fig. 6: DMA test curve of composite of banana particulate

4.2.3 TTS

Time temperature superposition (TTS) principle was used to predict the long term performance behaviour of the composites using the DMA machine. Williams-Landel-Ferry (WLF) model was used as the TTS equation (at frequencies of 1, 5 and 10Hz) where a master curve was generated depicting performance at extrapolated frequencies. Fig. 7 depicts the master

curve for composite of banana at 67°C. This was carried out under a load stress of 150KN/m^2. The curve shows the stiffness of the composite reduced to 0.21GPa (82% loss in stiffness) after about one (1) years (10^{-7}Hz). Fig. 8 depicts the master curve of the composite at 60°C with the stiffness reduced to 0.26GPa (78% loss in stiffness) after 32 years (10^{-9}Hz) of usage. Fig. 9 depicts the master curve of the composite at 50°C with the stiffness reduced to 0.71GPa (40% loss in stiffness) after 32 years (10^{-9}Hz) of usage. The stiffness could well be at 0.65GPa (45% loss) after 126 years ($4x10^{-9}$Hz). Fig. 10 depicts the master curve of the composite at 40°C with the stiffness reduced to 1.02GPa (14% loss in stiffness) after 32 years (10^{-9}Hz) of usage. The stiffness could well be at 1.01GPa (15% loss) after 126 years ($4x10^{-9}$Hz). Comparison of the master curves at different temperatures showed that the long term performance of the composite decreases with increase in temperature and that the lowest temperature of 40°C provides the best performance for a period of up to 126 years of usage. Subjecting the composite at a temperature less than 40°C is expected to further increase the stiffness performance of the composite within the same period. The composite is rheologically simple as it satisfied the WLF condition of a cole–cole plot i.e. the experimental points must lie close to a single curve (a neat single curve without outliers) as shown in Fig. 11 [37, 38].

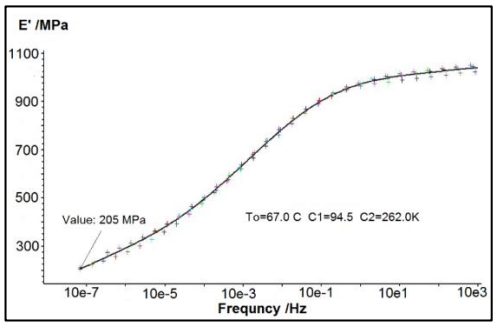

Fig. 7: Master curve of composite of banana particulate at 67°C

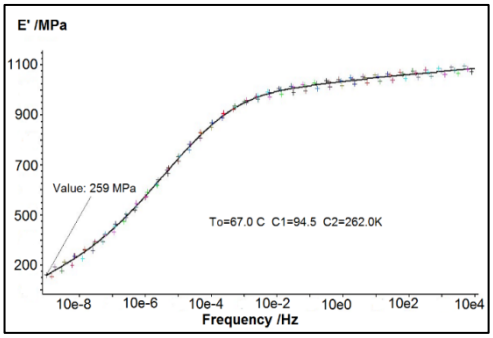

Fig. 8: Master curve of composite of banana particulate at 60°C

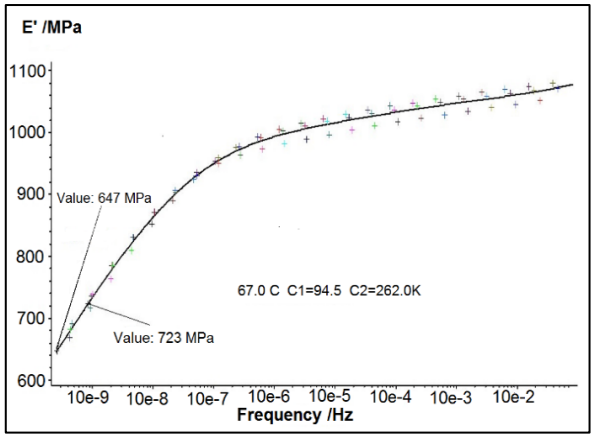

Fig. 9: Master curve of composite of banana particulate at 50°C

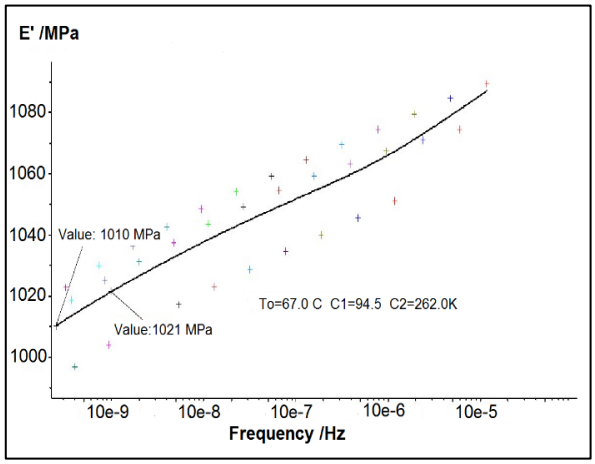

Fig. 10: Master curve of composite of banana particulate at 40°C

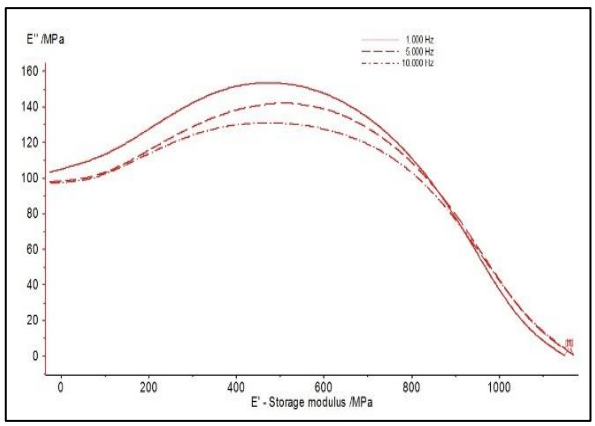

Fig. 11: Cole-cole of composite of banana particulate

4.3 Feasibility of Use as Piping Materials

The lifespan of the composite was determined using TTS at 50°C to be in excess of 126 years (4.2.3). The lifespan of PVC pipe

materials is about 100 years [39]. The lifespan of carbon steel pipe material is 30 – 40 years coupled corrosion and expensive maintenance cost [40, 41]. Considering that the composite is viscoelastic in nature, its potential for piping application is possible as it is not a direct load carrying component such as in ties, columns and beams where great amount of stresses are generated as a result of tension, compression and bending stresses respectively. Moreover, transportation of petroleum products is extensively carried out along a horizontal profile and thus the effects of weight of the moving fluid on the pipe is virtually negligible. The developed composite can therefore be employed in the area of transportation and distribution networks where higher temperatures of about 50ºC and above are rarely attained. Thus the composite can provide alternative potential material for piping application.

5. Conclusion

The composite was developed with low cost materials having an overall light-weight and good mechanical property. The optimum mechanical property was determined at 8, 72 and 20% formulation of banana stem particulates (reinforcement), PVC (matrix) and *Kankara* clay (filler) respectively, providing a corresponding density of 1.24g/cm^3 and tensile strength of 42MPa.

DMA curve showed that the composite has higher glass transition temperature and better mechanical (stiffness) stability at higher temperature under dynamic loading than PVC pipe. The composite has a higher glass transition temperature as compared with PVC pipe by 12.4ºC. The prediction at 50ºC showed that the composite has long term performance in excess of 100 years of usage. Comparison of the master curves at different temperatures showed that the long term performance of the composite decreases with increase in temperature. Thus the composite can provide alternative potential material for piping application.

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