Experimental Analysis of Mechanical Properties of Reinforced Polytetrafluoroethylene Composites

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ABSTRACT

In view of their high specific strength-to-weight ratio, fibre reinforced polymer composites have become substitutes for metals and their alloys for lightweight applications. The main key of this experimental analysis is to study the mechanical properties of reinforced polytetrafluoroethylene (PTFE) composites with inclusion of 25 wt. % carbon, 40 wt. % bronze and glass 25 wt. % fibres. The composites were prepared through compression moulding process. The Mechanical tests were conducted according to ASTM standards. The experimental analysis results revealed that addition of fibres into PTFE increased hardness of PTFE from 50 HRB to 62, 65 and 67 HRB for 25 wt. % glass, 25 wt. % carbon and 40 wt. % bronze fibres reinforced composites, respectively. Flexural strength of PTFE was also found to increase from 8.21 MPa to 20.50, 23.10 and 27.20 MPa, for 25 wt. % glass, 40 wt. % bronze and 25 wt. % carbon PTFE based composites, respectively. However, tensile strength decreased due to addition of fibres with 25 wt. % carbon fibre reinforced composite exhibiting the lowest tensile strength of 16.46 MPa when compared to the maximum tensile strength of PTFE (24.35 MPa).

Keywords: *PTFE. Carbon Fibre · Glass Fibre · Bronze Fibre · Mechanical Properties.*

1. Introduction

The quality and standard living of our lives is related polymer matrix composites (PMCs) [1]. PMCs are being increasingly used due to their low densities and exceptional strengths. In particular, fibres reinforced polymer composites are widely used in many sectors such as automotive, aerospace and aircraft industries [2]. Polytetrafluoroethylene (PTFE) is characterized by sterling properties such as wide range of service temperatures, high flammability resistance, high chemical inertness, low dielectric constant, high chemical resistance, low coefficient of friction and is inexpensive [3-4]. These sterling properties of PTFE have endeared it to many including aerospace, space and automotive industries. However, it shows poor mechanical properties such as low stiffness and non-resilient thereby restricting its advanced applications [5]. Consequently, PTFE is generally reinforced with fibres [6] thus producing enhanced PTFE based composites having high specific strength and specific rigidity lightweight and low density [7-8]. This reinforced PTFE composites are used as bearings, gears, bushing [9–11] and dental prosthetic [12]. In the design and development of PMCs, amounts, types, sizes as well as distribution of fibres are must be considered [13]. Equally important to the mechanical properties PMCs is the adhesion between matrix and fibres [14].

Several researchers have conducted investigations on the influence of various types of fibres on mechanical properties of polymers. Hemanth et al. [15] reinforced PTFE/TEC with glass fibre, alumina, and silicon and molybdenum disulphide. They found that addition of the fibres and particulates into PTFE/TCE increased hardness and tensile of the PTFE/TCE. The hardness increased from 10.1 HV to 11.4, 13.6 HV, and 12.5 HV for PTFE/TCE/glass fibre, PTFE/TCE/ceramic filler and PTFE/TCE/ceramic fillers/molybdenum disulphide, respectively. The tensile strength of the PTFE/TCE appreciated from 30.58 MPa to 57.84 MPa for PTFE/TCE/glass fibre, 30.16 MPa for PTFE/TCE/ceramic filler and 29.72 MPa for PTFE/TCE/ceramic fillers/molybdenum disulphide. Patil and Krishna [16] reported that addition of bronze 10-20 wt. % into epoxy with a constant amount of chopped E-glass fibre enhanced the tensile strength to 44.7 MPa from 40 MPa. Riul et al., [17] studied the mechanical properties of glass reinforced PTFE laminate. It was found that inclusion of glass fibre to PTFE increased the elastic modulus as well as the tensile strength to 14.2 GPa and 165 MPa from 0.59 GPa and 171 MPa, respectively. In order to improve the mechanical properties of PTFE Ronghao et al., [18] reinforced PTFE with carbon fibre (CF) containing carbon nano tube (CNT) and plasma-treated the composites. Results revealed that flexural and tensile strengths of PTFE/CF increased due to addition of the CNT and the plasma treatment. The increase in flexural strength was found to be 8% while that of the tensile strength was 192 MPa from 172 MPa. Yu et al., [19] studied the mechanical properties of continuous carbon fibre with concentric and isotropic infill patterns composites produced using additive manufacturing. The results revealed that composite having concentric carbon and infill pattern showed better tensile strength and flexural strength from 0.95 GPa and 69.06 MPa to 5.109 GPa to of 270.63 MPa, respectively. Oshima, Udagawa, and Morita [20] evaluated the performance of cross-linked PTFE as a potential matrix of PTFE filled with carbon fibre composites. The cross-linking of the PTFE was obtained by electron beam irradiation. The results of the study revealed that the flexural modulus as well as the flexural strength of the PTFE increased from 0.59 GPa and 17.6 MPa to 10.9 GPa and 42.6 MPa, respectively. Zhang et al., [21] studied the mechanical and tribological behaviours and microstructure of PTFE filled with carbon and aramid fibres in different scales. They found that addition of the fibres in different proportions decreased the tensile and impact strengths of the PTFE. The tensile strength Of PTFE decreased from 27.90 to 21.87 MPa when carbon fibre/MCNT of 7 µm at 0.5% was added while impact strength reduced from 17.89 to 8.61 Kjm-2 at 7 µm of 1% carbon/MCNT. However, elastic modulus of PTFE increased to 471.95 from 276.80 MPa. Okhlopkova et al., [22] investigated the influence of 1-5 wt. % carbon fibre on PTFE. The authors showed that tensile strength decreased with addition of carbon fibre from 20 MPa to 19, 18 for 2 wt. % and 3 wt. % of carbon fibre, respectively. However, the elastic modulus of PTFE increased from 440 MPa to 453, 481, 581, 528 and 554 MPa for 1, 2, 3, 4 and 5 wt. % of reinforced carbon fibre PTE composites, respectively. He, Chang and Huang [23] improved the mechanical properties of CF/PTFE composite by surface treatment. The surface treatment of CF/PTFE composites in the study was accomplished using vapour chemical deposition of graphene oxide onto the CF surface. The authors discovered that treated CF/PTFE composite increased interface shear strength (IFSS) and interlaminar shear strength (ILSS) from 45 and 50 MPa for untreated samples to 60 and 70 MPa for treated samples after 10 and 5 minutes, respectively. More so, tensile strength of untreated PTFE slightly increased from 3.75 to 3.91 GPa for treated CF/PTFE composite. Vasilev, Okhlopkova and Struchkova, [24] studied the effect of complex fillers of carbon fibre (CF), kaolin (Kl) and ultra-disperse (U) PTFE on reinforced PTFE composites. Kl and UPTFE were maintained at 1 wt. % while CF was varied in 1, 3 and 5 wt. %. Results revealed PTFE's tensile strength of 20 MPa decreased 19.10 and 19.40 MPa for PTFE + 1 wt. % CF + 1 wt. % Kl and PTFE + 1 wt. % CF + 1 wt. % Kl + 1 wt. % UPTFE, respectively. PTFE + 5 wt. % CF + 1 wt. % Kl + 1 wt. % UPTFE showed a tensile strength of 20.30 MPa. It is obvious from the results that the addition of the complex fillers had no signicant effect of PTFE. Mazur et al. [25] characterized PTEF based composites in which bronze particles and mineral fibres/particles were added to the PTFE. The introduction of individual fillers was as follows: glass fibres—15–25 wt. %, graphite particles—5 wt. % and bronze—30–60 wt. %, coke flakes—25 wt. %. The addition of the fibres increased the mechanical properties both at static and dynamic loading conditions. PTFE with 25 wt. % carbon fibre exhibited the maximum elastic modulus of 1292 MPa as compared to the pure PTFE of 766 MPa.

PTFE is one of the most promising as well as significant polymeric matrices. However, it shows poor mechanical properties. As a result, the objective of this study is to improve the mechanical strength of PTFE by adding carbon (C), bronze (B) and glass (G) fibres to the PTFE polymeric material and experimentally analyse the mechanical strength. The mechanical tests were performed based on ASTM standards.

2. Materials and Method

2.1 Materials

The natural recyclability of polymers is a strong motivation for their wide range of applications. In this experimental analysis, PTFE in powder form under the trade name of Teflon was used as matrix. Three kinds of fibres were used as reinforcement: bronze of particle size 65 µm, milled E-glass fibre with a nominal diameter of 13 µm length of 0.8 mm and amorphous petroleum-coke carbon having a particle size of <75 µm and a purity of 99%. All of these materials were produced and supplied by Polymer Chemical Industry Ltd. (Polikim A.S., Gebze, and Turkiye). The different percentage compositions, designations and colour of the materials used in this study was presented in Table 1.

Table 1. Materials and their percentage composition

Coded samples	Matrix (wt. %)	Filler (wt. %)	Colour
PTFE	100	-	White
G25	75	25	Grey
C25	75	25	Black
BF40	60	40	Brown

2.2 Fabrication

Mixing of PTFE powder and fibres was done by dry-mixing the matrix as well as the fibres in a paddle mixer. Rectangular samples with dimensions: (300 × 300 × 6) mm was fabricated for the tests by pressing in hydraulic presses. The blended matrix and fibres were dried at 60 °C for 24 hr followed by pressed at 70 MPa at room temperature. The samples were removed from the mould and were relaxed at ambient pressure and temperature for approximately 12 hr. before sintering. The parts formed in the pressing process, removed from the moulds or in the moulds, were sintered in furnaces with internal air circulation, at a temperature of 370 °C with a rate of 40 °Chr-1. The sintering process, depending on the weight of the product, takes up to 38 hr. Thereafter, the sintered products were cooled to room temperature in the oven at 40 °Chr-1. In Figure 1, a schematic diagram of the fabrication process was depicted.

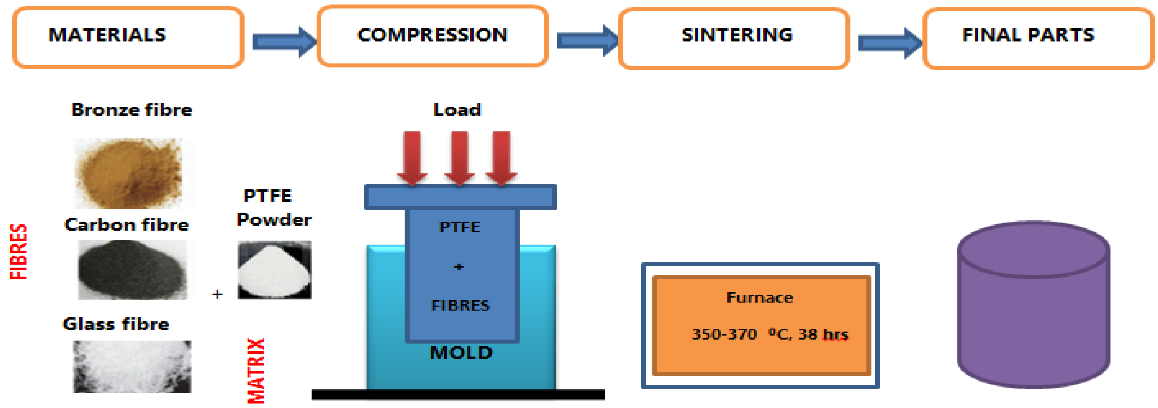


Figure 1. A schematic representation of the fabrication process

2.3 Hardness Test

The Rockwell hardness test of the four samples was performed as per ASTM D 785-03 standard using digital hardness tester (Model: THR-150D, New Delhi, ND, India) shown in Figure 2. The surfaces of the samples were polished by fine sand papers of 13 µm so that flat and smooth surfaces were obtained for accurate results. The unit and value of the hardness were defined by Rockwell hardness (HRB). The samples were indented at a constant load of 60 kg for a dwell time of 5 s. The indentation readings were taken at five different points on the samples. HRB values were automatically computed, displayed on the tester screen from where the readings were read and recorded. Mean values of the five readings were computed and used for analysis.

Figure 2. THR-150D digital hardness tester

2.4 Tensile Test

The determination of the tensile properties of samples was obtained in accordance with ASTM D638-14 Type I on Universal testing machine (Universal Testing Machine Lloyds, City, UK) with a capacity of 50 kN equipped with a load cell of 5 kN. The doge-bone shaped samples of 6 mm thick as shown in Figure 3(a) were tested at testing speed of 6 ± 1 mmmin-1. Prior to testing original width and thickness of samples at gauge length were measured at three different points using digital Vernia calliper. The original cross-sectional area (A0) was computed though the multiplication of the average width and average thickness of the samples. Five readings were taken and average reported for analysis. The engineering stress (σe) can be estimated through maximum applied force divided by the original cross-section of the samples as in Eq. 1 [19]. Similarly, the engineering strain (ϵe) can be computed via division of the change in length and original length Eq. 2 [19]. Samples for the test and deformations of some samples were shown in Figure 3.

$$\sigma e = \frac{F}{A_0} \qquad (MPa) \qquad (1)$$

$$\epsilon e = \frac{\Delta l}{l_0} \qquad (Dimensionless) \qquad (2)$$

where F = applied (N), $\mathrm{A_0}$ = original cross-sectional area (mm2), Δl = change in length (mm), and ($\mathrm{l_0}$) = original gage length ($\mathrm{l_0}$).

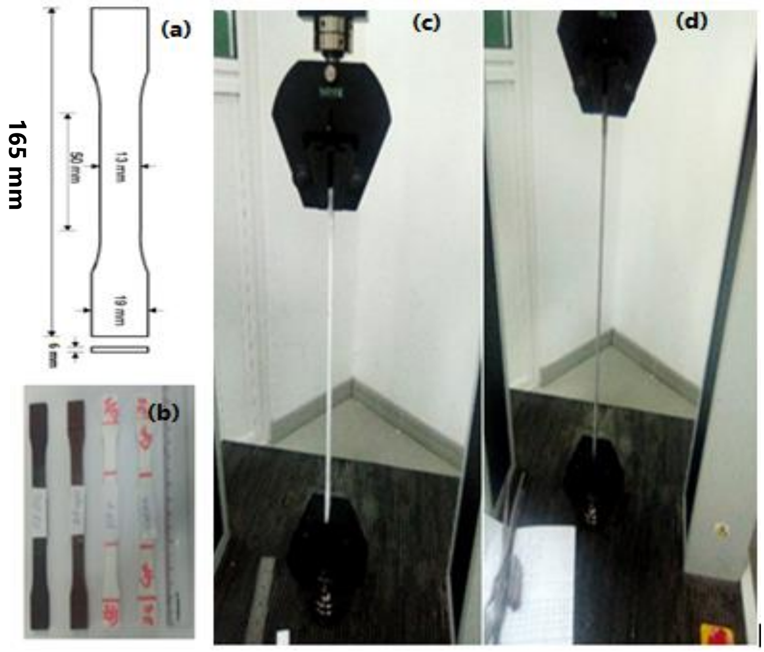


Figure 3. (a) standard tension sample dimensions, (b) the samples, (c) deformations of PTFE (d) B40 composites

2.5 Flexural test

The flexural properties of the materials were determined by three-point bending test according to ASTM D 790-03 standard using Universal Testing Machine (Lloyds, with a capacity of 50 kN equipped with a load cell 5 kN). The test was conducted on five samples of each class of material having dimension of 115.2

mm × 28.8 mm × 6 mm as provided in Figure 4(a) while Figure 4(b) showed the set up. For all the experiments, support span to depth ratio of 16:1 and cross head speed of 1 mmmin-1 at room temperature were maintained. The average value of five data points was taken as results. The load was applied at the centre of the samples until maximum bending was obtained. During the test, the applied load was recorded by a computer attached to the machine. The bending properties of PTFE and its composites were determined as provided below.

The flexural strength or stress (σ_f) was computed using equation (5) [19]:

$$\sigma_f = \frac{3FL}{2bd^2} \qquad (\mathrm{MPa}) \qquad (5)$$

The flexural modulus of elasticity (E_f) in bending was calculated according to equation (6) [19]:

$$E_f = \frac{L^3 m}{4bd^3} \qquad (\mathrm{MPa}) \qquad (6)$$

where F= load (N), L = support span (mm), b = width (mm), d= depth mm, m = slope of the tangent to the initial straight-line portion of the load-deflection curve (Nmm-1) of deflection.

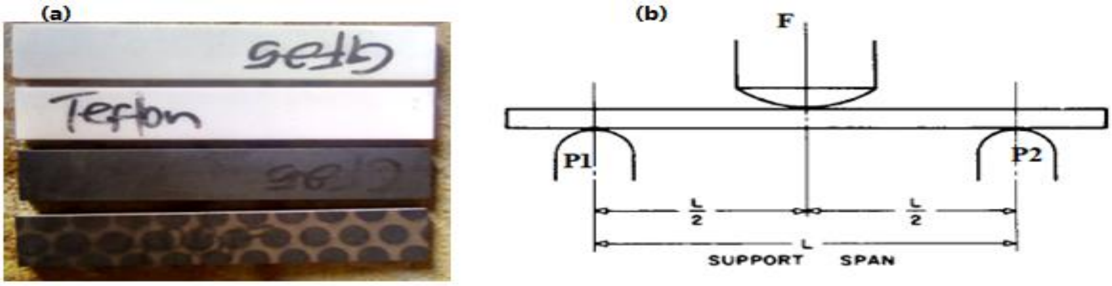


Figure 4. (a) Samples for flexural test and (b) schematic set up for the test

3. Results and Discussion

3.1 Hardness

Hardness experiment has been carried out on neat PTFE and fibres reinforced PTFE composites. Figure 5 showed that the hardness values of the unreinforced PTFE composites increased with incorporation of carbon, glass and bronze fibres in weight percentages but in the case of neat PTFE matrix the hardness decreased. The increase in hardness of PTFE matrix increased to about 24%, 30% and 34% for G25, C25, and B40 composites, respectively. This is attributed to rigidity, brittleness and stiffness of the fibres and decrease in inter-fibre distance in the PTFE matrix which led to increase of the composites against indentation. The fibre reinforced PTFE composites indicated their better hardness compared to unreinforced PTFE. Similar results were reported in [17, 26]. Figure 5 also revealed that BF40 composite has exhibited the maximum hardness value of 67 HRB. This was explained on account of bronze fibre wt. % which is greater than that of carbon and glass reinforced composites.

3.2 Tensile strength

Equation (1) was used to compute the tensile strength (engineering stress) of the materials in the study. Figure 6 depicted the effect of fibres on neat PTFE and its composites. It can be clearly seen that the tensile strength of PTFE decreased with inclusion of fibres into unreinforced PTFE matrix. This decrease in engineering stress of the PTFE was around 32.04 % for C25, 27.56 % for G25 and 11.12 % for B40 composites. PTFE higher engineering stress in comparison to C25, G25 and B40 composites was attributed to movement of molecules of PTFE which enabled it to transfer the tensile loading to its neighbouring molecules. PTFE as a thermoplastic polymer is ductile and thus can undergo appreciable elongation. The decrease in engineering stress of PTFE due addition of fibres might be attributed to weak adhesion between the fibres and unreinforced PTFE. PTFE is also known to have weak chemical reactivity and low coefficient of friction that reduces the mechanical interaction between PTFE and fibres. Another reason for decrease in engineering stress of PTFE is the brittleness and hardness of the fibres. Here, the fibres acted as molecular chain alignment inhibitors that impeded slip of PTFE macromolecules chain thereby rendering the PTFE brittle from its ductile nature. In addition, fibres lying embedded in the precursor caused stress to be raised in reinforced polymer composites thereby making it easier defects to be created in the polymer based composites [28]. From the results obtained CF25 composite indicated the lowest tensile strength of 16.46 MPa compared to the other composites. This could be attributed to not achieving enough interface-bonding between PTFE and C but which is mostly the responsible mechanism coming from neat PTFE due to lower surface energy. In general, adhesion behaviour is lower for making composite with PTFE. Thus, the surface properties of unreinforced PTFE can be searched to improve the surface free energy and adhesion property.

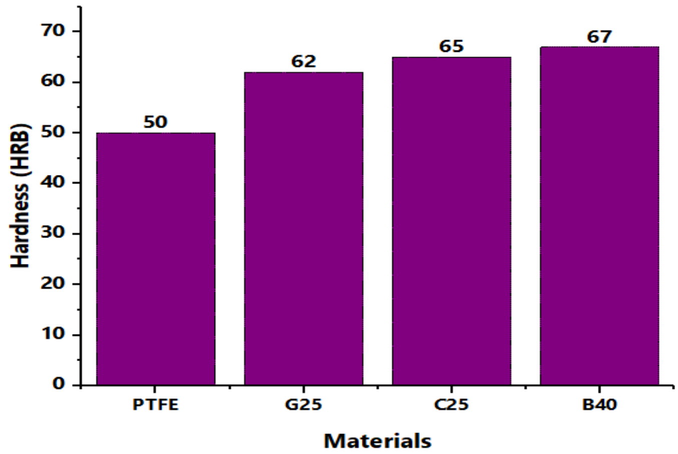


Figure 5. Hardness for the investigated materials

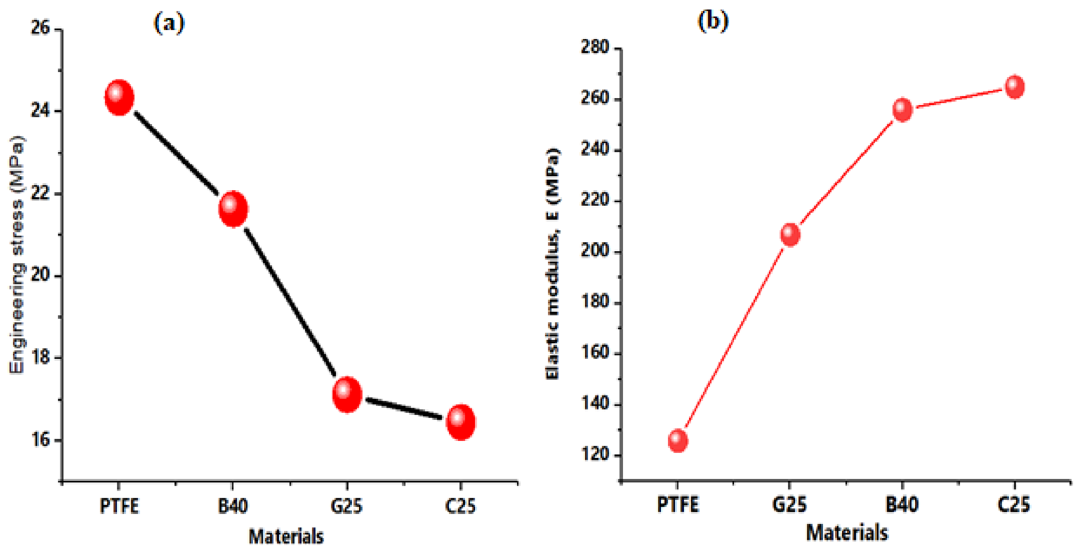


Figure 6. (a) Tensile strength of the samples and (b) Elastic modulus of samples

In terms of the elastic modulus (E) PTFE experienced significant increase as shown in Figure 7. Elastic modulus is a function of fibre volume fraction, stiffness, orientation of fibres and matrix stiffness. The increase in elastic modulus was due to brittleness and hardness nature and amounts of fibres. More so, the non-dependence of E on interfacial strength unless there exists an appreciable amount of slippage at the matrix–fibre interface accounted for the increase in the E of PTFE [29]. From the experimental outcomes obtained CF25 composite has indicated the highest elastic modulus (265 MPa). Figure 7 shows the broken samples of the study. It is clear that the materials failed at different positions. Some broke at the edge while others at the middle.

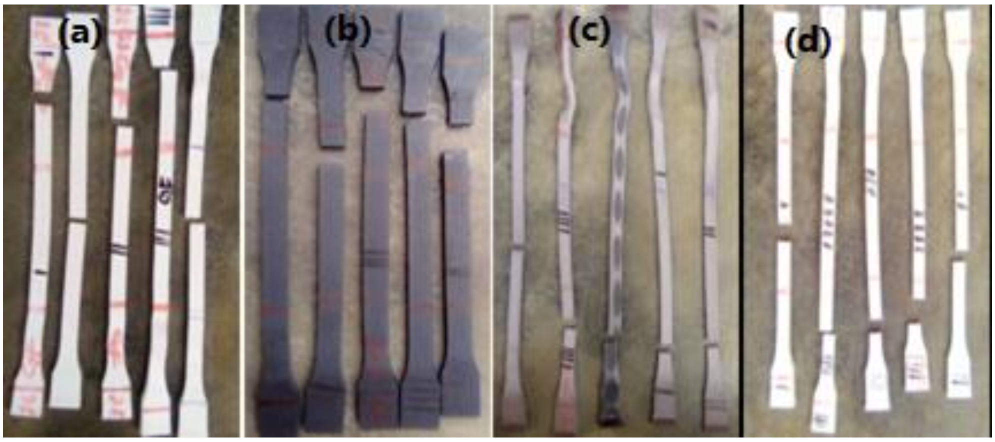


Figure 7. Fractured samples of (a) G25, (b) C25, (c) B40 composites and (d) PTFE after tensile testing

3.2 Engineering strain (EƐ)

The engineering strain of the materials has been computed through equation 2. Comparison of strains PTFE as well as reinforced PTFE composites was shown in Figure 8 (a). It was obvious in Figure 8 (a) that the engineering strain of PTFE decreased with addition of carbon fibre on one hand but increased with addition bronze and glass fibres. The decrease is related to carbon fibre acting as inhibitor to the continuity motion of PTFE molecular chains. The increase in engineering strain of PTFE due to addition of glass and bronze fibres was explained on the basis that the glass as well as the bronze fibres assisted PTFE molecular chain motion up to the maximum engineering strain. This finding was supported by the work of Wang et al. [27]. Additionally, Figure 8 (b) showed the engineering stress-strain curve of the reinforced PTFE composites. As seen (Figure 8(b)) all the materials experienced sudden fracture after attaining the maximum engineering stress. More so, as seen in Figure 8(b), engineering strain at fracture of PTFE increased from 4.69 4.69 to 7.50 and 6.09 due to inclusion of 40 wt. % B and 25 wt. % G into PTFE, respectively.

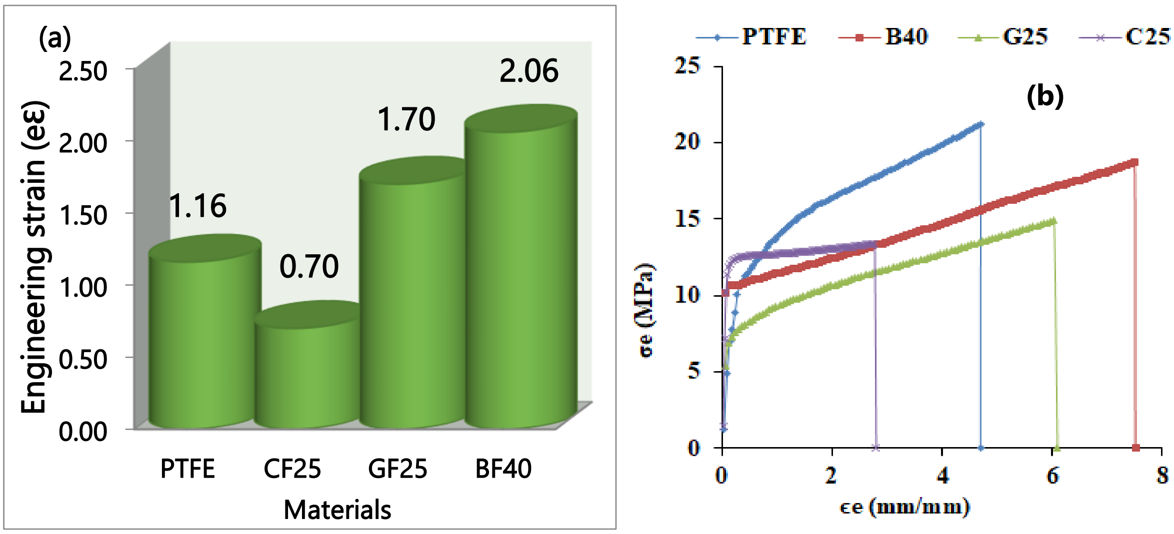


Figure 8. (a) Engineering strain values and (b) engineering stress–strain curve for the samples

3.2. Flexural Properties

Flexural properties describe flexibility of materials. Good flexural strength implies materials with high hardness and stiffness. Table 2 shows the flexural strength and flexural modulus values obtained for PTFE and its composites using Equations (5) and (6), respectively. There was no fracture of PTFE and its composites after reaching the maximum load but experienced deformation as shown in Figure 12(a). As seen in Table 2, flexural strength of PTFE was found as 8.21 MPa. However, with incorporation of 25 wt. % G, 40 wt. % B, and 25 wt. %

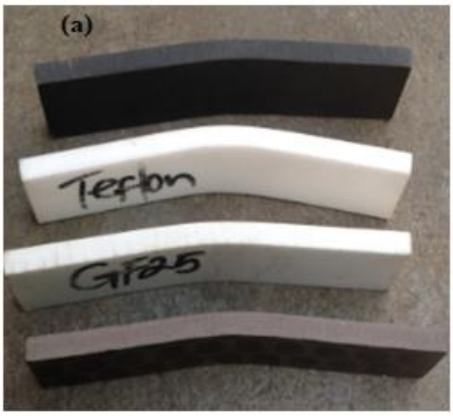
C fibres were into PTFE flexural strength of unreinforced PTFE increased from 8.21 MPa to 20.5 MPa, 23.1 MPa and 27.2 MPa, respectively. More so, similar trend was noticed for flexural modulus of PTFE improving from 371 MPa to 1194, 1303, and 1365 MPa for G25, B40 and C25, respectively.

Table 2. Flexural properties of the PTFE-reinforced composites

Materials	Flexural strength (MPa)	Flexural modulus (MPa)
PTFE	8.21	371
GF25	20.5	1414
BF40	23.1	1769
CF25	27.2	2162

This increase in flexural properties of virgin PTFE matrix was due to good compatibility between fibres and neat PTFE. More so, uniform distribution of fibres as well as strong adhesion between the reinforcing phases and virgin PTFE also accounted for the improved flexural strength of PTFE. This is in agreement with literature data found in [30-31] that good matrix-fibre adhesion results in better flexural strength of PMCs.

Figure 12(b) showed the flexural strength–strain curve for the investigated materials. It can be seen from Figure 12(b) that PTFE, GF25 and CF25 specimens failed at almost the same strain of about 0.18. This implies that addition of carbon and glass fibres did not significantly influence PTFE matrix strain. However, in the case of BF40 composite the strain was higher. Its curve after reaching a strain of about 0.18 continued to strain up to about 0.4 showing significant effect on PTFE strain. Traditionally, strain at break depreciates due to introduction of reinforcements into matrices. Due to natural rigidity of fibres, deformation is mostly contributed by matrices and the real deformation is felt by the matrices. The lower strain of the C25 and G25 composites is as a result of the fibres acting as inhibitors to motion of PTFE molecular chain. The fibres caused discontinuity of PTFE matrix molecular chain thereby causing molecular chain misalignment. The increase in strain of PTFE on addition 40 wt. % of bronze fibre might be due to using larger particles, which is about 65 μm in size and the bronze fibre being ductile and possibly assisting the motion of PTFE matrix molecules motion, thus leading to alignment of molecular chain of PTFE. This contradicted established theory that addition of more loadings of fibres into polymers reduces their strain rate. Similar findings were found and reported by [28, 32-33].



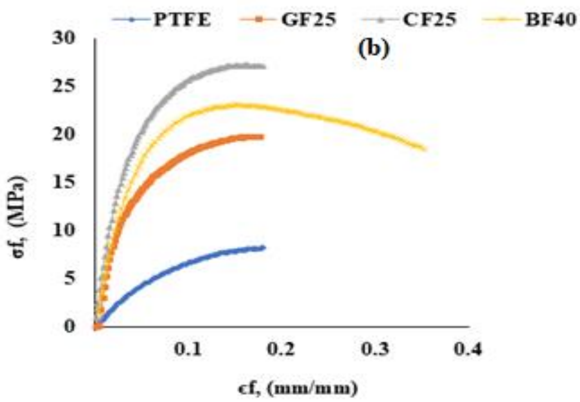


Figure 12. (a) Failed samples after bending test and (b) σf versus ϵf curve of the tested samples

3. Conclusion

The objective of this study is to experimentally analyse the effect of commonly used fibres on the mechanical properties of unreinforced polytetrafluoroethylene (PTFE) matrix. According to the mechanical experimental results performed, the following conclusions were drawn:

1. The addition of carbon, bronze and glass fibres into PTFE increased the PTFE's hardness by 24%, 30%, and 34%, respectively.
2. Elastic modulus increased when carbon, bronze and glass fibres were added to PTFE.

3. However, the tensile strength of PTFE decreased due to incorporation of carbon, bronze and glass fibres to the PTFE by 32.04 % for C25, 27.56 % for G25 and 11.12 % for B40 composites respectively.
4. PTFE increased from 8.21 MPa to 20.5 MPa, 23.1 MPa and 27.2 MPa, respectively. Similarly, the same trend was noticed for flexural modulus of PTFE improving from 371 MPa to 1194 for G25, 1303 for B40, and 1365 MPa for C25 composites.

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