Analysis of mechanical properties of randomly oriented phenol composites

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Receiving Date: 16-09-2010 **- Accept Date:** 21-06-2011

Abstract

Tensile strength, compression strength, bending strength, and fracture toughness of phenol formaldehyde type novolac resin (PFN) reinforced with randomly-oriented different fibers as well as powders in terms of mechanical properties, which are subject to change in different additives volume fraction have been studied. Tensile strength, σ_T , results show that σ_T increases with the increasing volume fraction of additives. Failures display two mechanisms according to the kind of additives. Where, it can be observed, pullout mechanism with respect to fibers composites, and rupture mechanism with respect to powder fillers composites. Compression strength, σ_c , results show that σ_c increases with the increasing volume fraction of additives. Bending strength, σ_f, results show, that σ_f increases progressively by succession of volume fraction of fibers. Fracture toughness G_c , results show that G_c increased with increasing of volume fraction of additives. Failure takes place through two mechanisms, according to additives kind. Where, the failure takes place by pullout mechanism with respect to fibers composites, and by pining mechanism with respect to powder fillers composites.

***Keywords*:** Phenol composites, tensile, compression, bending, and fracture toughness.

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1. Introduction

Materials that are utilized in high technology applications are some times termed advanced materials. By high technology, we mean a device or product that operates or functions using relatively intricate and sophisticated principles. Examples include electronic equipment; computers, fiber-optic system, spacecraft, aircraft, and military rocketry. These advanced materials are typically either traditional material whose properties have been enhanced, or newly developed high-performance materials. Furthermore, they may be of all material types (e.g. metals, ceramics, polymers), and are normally relatively expensive [1].

Since phenolic resins have a wide range of application, a lot of researchers pay attention how to alter preparation conditions to enhance resin's properties. Increased attention has been paid in recent years to the research on polymer composites in general and phenolic composites in particular, from the point of view of their potential uses in mechanical, optical, electrical, thermal and ablative applications [2,3,4,5].

Composites which has high volume fraction of additives [6] can be used in applications, which need relatively high tensile strength, high compressive strength, high bending strength and high resistance of impact. In this work, tensile strength, compression strength bending strength, and fracture toughness, for phenolic (phenol- formaldehyde) resin, type novolac PFN reinforced with different fibers and different powder fillers have been studied, in terms of, mechanical properties, which are subject to change in different fibers-powder fillers volume fraction.

2. Theoretical approach

Let us consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction of fiber alignment direction. First of all, it is assumed that the fiber-matrix interfacial bond is very good, such that deformation of both matrix and fibers is the same (an isostrain situation). Under these conditions, the total load sustained by the composite F_c is equal to the loads carried by the matrix phase F_m and the fiber phase F_f. or [7]:

$$F_c = F_m + F_f \quad \text{.....(1)}$$

From the definition of stress, equation, $F = \sigma A$: and thus expressions for F_c, F_m, and F_f in terms of their respective stresses (σ_c, σ_m, and σ_f) and cross-sectional areas (A_c,A_m, and A_f) are possible. Substitution of these into equation (1) yields:

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad \text{.....(2)}$$

and then, dividing through by the total cross-sectional area of the composite, A_c, we have:

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c} \quad \text{.....(3)}$$

where A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases, respectively. If the composite, matrix, and fiber phase lengths are all equal, A_m/A_c is equivalent to the volume fraction of the matrix, V_m: and likewise for the fibers, $V_f = A_f/A_c$. Equation (3) now becomes:

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad \text{.....(4)}$$

the previous assumption of an isostrain state means that:

$$\varepsilon_c = \varepsilon_m = \varepsilon_f \quad \text{.....(5)}$$

and when each term in equation (4) is divided by its respective strain,

$$\frac{\sigma_c}{\varepsilon_c} = \frac{\sigma_m}{\varepsilon_m} V_m + \frac{\sigma_f}{\varepsilon_f} V_f \quad \text{.....(6)}$$

Furthermore, if composite, matrix, and fiber deformations are all elastic, then $\sigma_c / \varepsilon_c = E_c$, $\sigma_m / \varepsilon_m = E_m$, and $\sigma_f / \varepsilon_f = E_f$,the E's being the moduli of elasticity for the respective phases. Substitution into equation (6) yields an expression for the modulus of elasticity of a continuous and aligned fibrous composite in the direction of alignment (or longitudinal direction). E_{cl}, as [8]:

$$E_{cl} = E_m V_m + E_f V_f \quad \text{.....(7a)}$$

or

$$E_{cl} = E_m (1 - V_f) + E_f V_f \quad \text{.....(7b)}$$

since the composite consists of only matrix and fiber phases : that is,

$$V_m + V_f = 1.$$

Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases. Other properties, including density, also have this dependence on volume fractions. Equation (7a) is the fiber analogue of equation (7c) the upper bound for particle-reinforced composites:

$$E_c(u) = E_m V_m + E_p V_p \quad \text{.....(7c)}$$

It can also be shown, for longitudinal loading, that the ratio of load carried by the fibers to that carried by the matrix is [9]:

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \quad \text{.....(8)}$$

A continuous and oriented fiber composite may be loaded in the transverse direction: that is. The load is applied at a 90º angle to the direction of fiber alignment. For this situation the stress, σ, to which the composite as well as both phases are exposed, is the same, or :

$$\sigma_c = \sigma_m = \sigma_f = \sigma \quad \text{.....(9)}$$

This is termed an isostress state. Also, the strain or deformation of the entire composite, ε_c , is:

$$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f \quad \text{.....(10)}$$

but, since, $\varepsilon = \sigma / E$,

$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f \quad \text{.....(11)}$$

where E_{ct} is the modulus of elasticity in the transverse direction. Now, dividing through by, σ , yields:

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \quad \text{.....(12)}$$

this reduces to

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f) E_f + V_f E_m} \quad \text{.....(13)}$$

equation (13) is analogous to the lower-bound expression for particulate composites:

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \quad \text{.....(14)}$$

In these expressions, E and V denote the elastic modulus and volume fraction, respectively, whereas the subscripts c, m, and p represent composite, matrix, and particulate phases.

Randomly reinforced short-fiber composites will usually be isotropic: furthermore, their compression and tensile strengths will be similar. If all of the fibers happen to be aligned in the direction of compression, however, failure will often occur at stresses lower than the tensile failure stress. In composites with poor fiber/matrix bonding, longitudinal splitting will occur when the lateral tensile forces induced by the Poisson expansion exceed the interfacial tensile bond strength. In a well-bonded composite, a substantial proportion of the tensile strength may also, be attained in compression, but since the matrix is called upon to bear, a large fraction of the applied load, and since the reinforcement is not continuous, local shear failure in the matrix will initiate a buckling type of rupture, as the interface begins to fail, and fiber strengthening of the matrix is lost. A somewhat similar situation for continuously reinforced composites tested in compression has been treated theoretically [10].

When a free standing cylinder of a unidirectional composite is loaded in compression parallel with the fibers, the mode of failure depends on the strength of the fiber/resin bond. If the bond is weak, fibers debond from the matrix at low loads and the compression strength never reaches the same level as the tensile strength. Another complication in composites with brittle matrices is that if lateral spread is not prevented longitudinal cracks may be initiated near the loading platens which split the composite parallel with the fibers, and it is always necessary to ensure that the fibers are well aligned if premature buckling failures are to be avoided. For these reasons results reported from early experimental programmers seldom reflected the true composite compression strength, and measured values were rarely as high as the corresponding tensile strengths [10].

The modulus measures the resistance of a material to elastic deformation, for linear elastic materials the stress σ is related to the strain ε by Young's modulus E (Hook's law).

$$E = \left(\frac{Mass}{Deflection}\right)\left(\frac{gL^3}{48I}\right) \quad \text{.....(15)}$$

$$I = \frac{dB^3}{12} \quad \text{.....(16)}$$

Where: I =Engineering bending momentum, d = width of samples, B = thickness of sample, g = gravity, L = sample length.

$\left(\frac{Mass}{Deflection}\right)$ Is the slope of linear part of mass deflection curve obtained from three point bending load tests [11].

The flexural strength of a material is its ability to bend before it breaks. It is obtained when the ultimate flexibility of one material is achieved before its proportional limit [12].

Flexural forces are the result of forces the flexural test measures behavior of materials when subjected to simple beam loading. It is also called a transverse beam test with some materials. Maximum fiber stress and maximum strain are calculated for increments of load. Flexural strength is defined as the maximum stress in the outermost fiber. It is obtained when the ultimate flexibility of one material is achieved before its proportional limit. Specimens are placed on two supports and a load is applied at the center, this test is known as three-point bending test. Flexural modulus is calculated from the slope of the stress against deflection curve [13]. The load at yield is the sample material's flexural strength that is calculated by the following formula [12]:

$$\sigma_f = \frac{3PL}{2bh^2} \quad \text{.....(17)}$$

Where: P= the ultimate load at fracture, l= the distance of the supports, b= the width of the specimen, d= the thickness of the specimen.

The work of fracture or fracture energy (W) can be defined as the total work required to fracture a sample, per unit area of new surface produced whether it is in a Charpy or Izod test, or in a slow three points fracture test [10]. It is usually necessary, however, if these comparisons are to be valid, for samples to contain a sharp notch whose depth, c, is in proportion of the specimen thickness, *D*. The impact fracture energy, G_c, then is defined as [10]:

$$G_c = \frac{2W}{A} \qquad (18)$$

where W is the energy absorbed from the pendulum and A is cross sectional area of the fracture ligament . The factor 2 in Eq. (18) arises because the average crack tip displacement in bending is one-half the crack tip displacement in tension.

The work of fracture, γ_F, was calculated from the following equation [14]:

$$\gamma_F = \frac{W}{2B(D-c)} \qquad (19)$$

B is the specimen width. For a number of reasons concerned with the calculation of stresses around a crack and the development of the theory of linear elastic fracture mechanics, it is convenient to define a parameter known as the “fracture Toughness”. Fracture occurs when this parameter reaches a critical value K_c:

$$K_c^2 = E\, G_c, \qquad (20)$$

where, E, is young modulus in GPa.

3. Experimental approach

The matrix of the composites in our work is pure phenolic resin type novolac (PFN). The randomly oriented additives investigated in this work are six groups; S- glass fiber composites (SGFC), E- glass fiber composites (EGFC), basalt rock fiber composites (BRFC), silica powder composites (SPC), basalt powder composites (BPC), and alumina powder composites (APC). Hot-press technique was used to prepare composites as well as novolac specimens at standard conditions.

Novolac in form of liquid was dried in an electric oven at (323 K) for 3hr. to obtain the novolac in form of solid, followed by milling to a desirable size suitable for molding operation. Novolac, which was prepared by this method, was used to prepare a reference specimens according to different types of testing standard requirement. Novolac in form of liquid was solved using ethanol to obtain a suitable matrix. At same time, fibers, which were used (EGF, SGF, and BRF), were dried in an electric oven at (393 K) for 3hr. to reduce humidity and activation its porosity. Then fibers were impregnated in matrix, which was prepared as above, followed by drying the mixture in air using dispersion method on a dry plate for 3hr. The mixture was pre- cured using an oven at (353 K) for 3hr. Hot–press technique was used in this work to prepare the composites specimens of PFR matrix, using flash mold.

Instron machine was used to calculate tensile strength as well as compression strength according to ASTM-D638-87b and ASTM-D659-85 respectively. Three point Test machine was used to measure bending strength according to ASTM-D790-86. The impact testing machine (pendulum type hammer) was used in Charpy impact mode to calculate fracture toughness according to ISO 79.

4. Results and Discussion

Figure (1) shows the influence of fibers vol.% (SGF, EGF, and BRF) on the tensile strength of PFN composites. From the Figure, it can be observed linear relationship between volume fraction of fibers and tensile strength values. Tensile strength values have been evidenced, that the composites were behaved as brittle materials, and that supporting by photographs and microscopes of composites. Tensile strength values coming as follow; the highest value for BRFC group, which is reached (287.1 MPa), then for SGFC group, which is reached (263.38 MPa), and then for EGFC group, which is reached (232 MPa), that is according to type of fibers and interface forces between the matrix and the fibers.

Figure (2) shows the influence of powder fillers vol.% of (SP,BP, and AP) on the tensile strength of PFN composites. From the Figure, it can be shown, that the tensile strength values, of BPC group were very high, reached (216.3 MPa), comparing with APC group, which reached (130.6 MPa), and SPC group, which reached (79.43 MPa).From the Figure, it can be shown, that the BPC curve has been behaved as linear behavior (i.e., increment of volume fraction lead to increasing in tensile strength). While, the results of SPC and APC groups were to be just same to same in behavior, which were had a constant proportional representation in tensile strength with increment of volume fraction of powder fillers.

Figure (3) explains the effect of volume fraction of fibers (SGF, EGF, and BRF) on the compression strength for the PFN matrix. From the Figure, mentioned above, it can be noticed, the compression strength values for the composites (SGFC and EGFC) are reached 297.26 MPa and 264.6 MPa respectively, while the BRFC group obtained the value 300 MPa as the highest value. It was found, that the resin material reinforced with fibers has relatively high resistance against compression loading when compared with a resin alone, the reason for this is attributed to that the material which is reinforced with short fibers are distributed randomly, so that, it has isotropic properties in all directions. If all fibers are aligned in the direction of compression forces, the collapse will occurred in the material, in stresses well below failure stresses. It was found that, the composite materials, which have weak inter-connection bonds, have weak resistance against compression loading, which is attributed to the occurrence of longitudinal splitting, when lateral tensile forces originated from Poisson expansion overcome the inter-connecting tension forces.

The effect of volume fraction of powder fillers on compression resistance of the PFR matrix is shown in Figure (4). From this Figure, it can be noticed a difference in the behavior of (SP,

BP, and AP) particles curve, where BPC group has the highest value for compression strength reaching 340.8 MPa. The behavior of the curve was linear and proportional to the volume fraction and compression strength. The two groups SPC and APC have the same behavior and have compression strength values of 102.9 MPa, 161.7 MPa respectively. Two kinds of mechanisms occur in different sites at the same time and are responsible for the occurrence of this kind of failure in the composite material (fiber reinforced or particle ceramic reinforced), that are the failure because of compression stresses and shear stresses failure. Customarily, the primary failure, in the specimen, was undergoing compression test on the external surface of specimen compressive-side surface. It was found that it is probable that the failure will occur in the composite material by the effect of compressive stresses, which will lead to the occurrence of buckling phenomenon in the matrix material or fibers (if the material is reinforced with fibers).

Flexural strength results were shown in Fig.(5) and (6). Generally, reinforcement by fibers leads to the increasing of flexural strength values with the increasing volume fraction This increment was differentiated in PFN composites depending on capability of strength of fibers, which depends on type, length, and orientation of fibers, with respect to the load. Influence of interface between the matrix and the reinforcement materials was clearly observed on flexural strength. From this figure, it can be seen that the behavior of flexural strength curves of novolac composites are similar to others and the failure is done by pullout mechanism. But the highest value it was for fibers group which was reached (270 MPa), than powders group (159.4 MPa), because the strength of fibers composites are greater than the strength of powders composites. Addition of powder fillers to the polymer matrix lead to increment of strength that can be explained via returning to the different mechanisms, which is depended on the bonding type between the particles and the matrix. First mechanism; represented the weak bonding case between the two phases of composite. In this case, the stress was regulated through the composite material, and it is transfer between the two phases of the material via friction mechanism. The second mechanism; represented the good bonding case between the two phases of composite, In this case, the strain was regulated through the composite material, and the stress was transferred via shearing mechanism. Encounter of crack with the particles, during its progressive through, the composite material, lead to creation of hindrance of its movement from this particles, which represented the obstacles front of the crack, works as a fixed positions at particle existence. To exceed the crack for this obstacles, and to

continue in its growth, it well be changed of its configuration and exchange to groups of elliptical secondary cracks, attempt to transfer between the particles. That lead to increment in crack surface, so, the energy requirement was increased to take place the fracture. In other word, the energy, which is given to the crack to propagate, will be distributed between the propagation of elliptical secondary cracks changing of origin crack configuration, and to exceed the obstacles, instead of exploit it to propagate the crack only.

Influence of fiber vol.% of (SGF, EGF, and BRF) on the fracture toughness of PFR was shown in Figure (7). From the Figure it can be seen that the behavior of fracture toughness curves of PFR composites similar to others. But the highest value it was for BRFC which is reached (302 KJ / m^2), then EGFC (240 KJ / m^2), and then SGFC (170 KJ /m^2). Explanation of fracture toughness results from the point of work of fracture, where, if un notch specimen of a relatively brittle material is loaded to failure in impact test, it will usually break catastrophically into several pieces, and the elastic energy, stored in the specimen is dissipated in a number of ways. Some is used up acoustically in the generation of noise, some in the kinetic energy of the pieces as they fly about the laboratory, and some is absorbed in the testing machine. Apart from these extraneous energy losses, some of the energy is absorbed by micromechanical processes which occur within the material in the vicinity of the fracture surfaces. Further, more, a material that normally fails catastrophically can be induced to fail in a quasi-controlled or completely controlled manner.

Figure (8) shows influence of powder filler vol.% of (SP, BP, and AP) on the fracture toughness of PFR matrix. From the Figure we can see that, a maximum value of fracture toughness was for APC group (120 KJ / m^2), then for BPC group (80 KJ / m^2), and then for SPC group (22 KJ / m^2). All the increases in fracture toughness which have been observed on adding powder fillers (SP, BP, and AP) have occurred when the filler is added to a low fracture toughness resin (like PFR). This can be explained as: when a crack propagates in a brittle material, second phase in homogeneities act as obstacles, which can impede the moving crack. This effect can often be directly observed by studying fracture surface features. During fracture, steps can be formed on the fracture surface as different sections of the crack front propagate on different, parallel planes. As the crack propagates the crack front tends to move onto a single plane and the steps coalesce to form characteristic “river’ markings. The steps so formed are perpendicular to the moving crack front and by using the pattern of the river markings on a fracture surface.

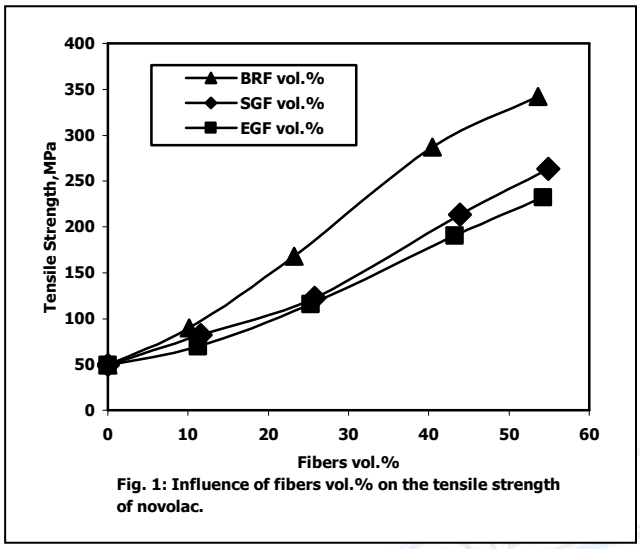

Fig. 1: Influence of fibers vol.% on the tensile strength of novolac.

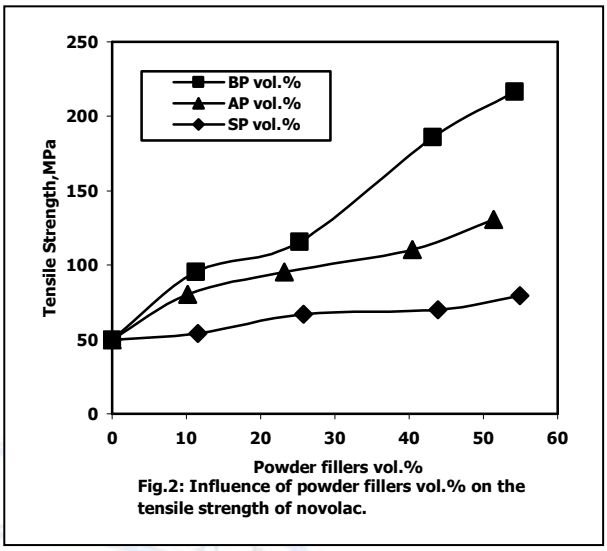

Fig.2: Influence of powder fillers vol.% on the tensile strength of novolac.

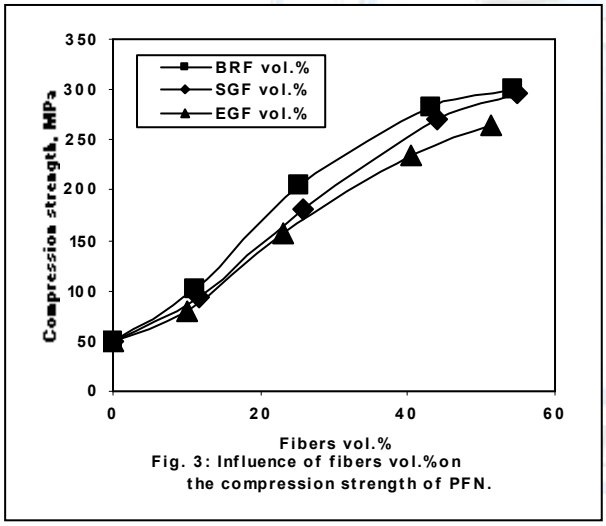

Fig. 3: Influence of fibers vol.%on the compression strength of PFN.

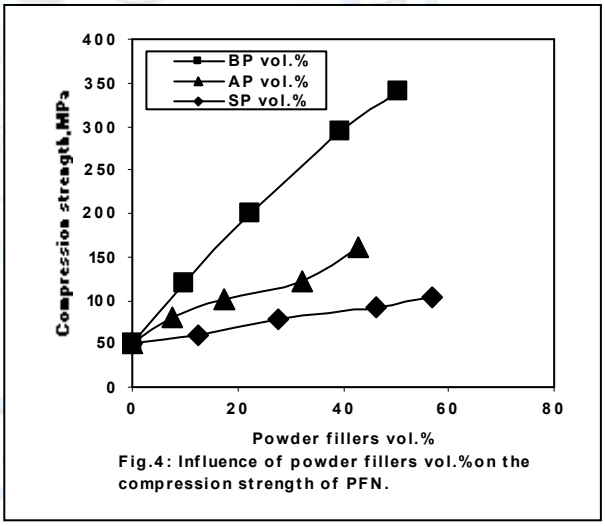

Fig.4: Influence of powder fillers vol.%on the compression strength of PFN.

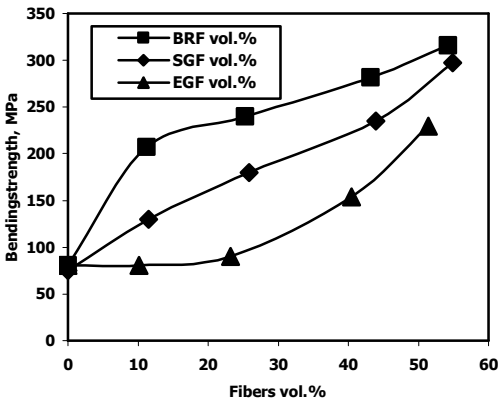

Fig. 5: Influence of fibers vol.% on the bending strength of PFN.

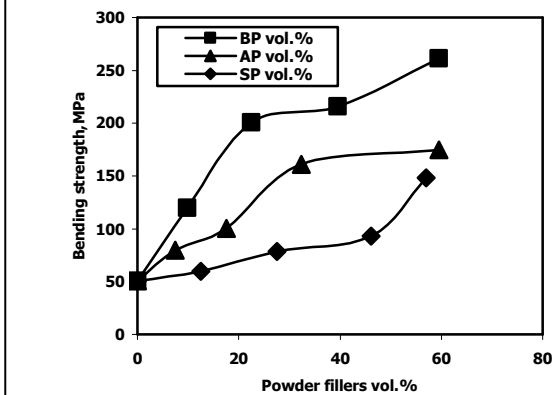

Fig.6: Influence of powder fillers vol.% on the bending strength of PFN.

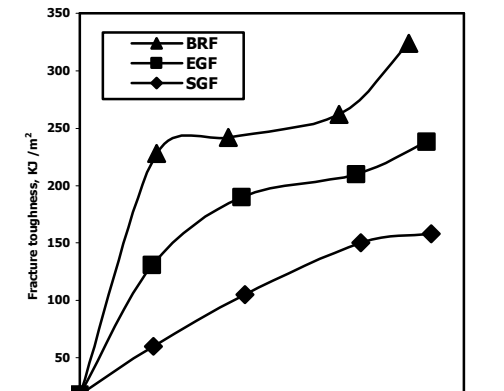

Fig. 7: Influence of fibers volume fraction on the fracture toughness of novolac.

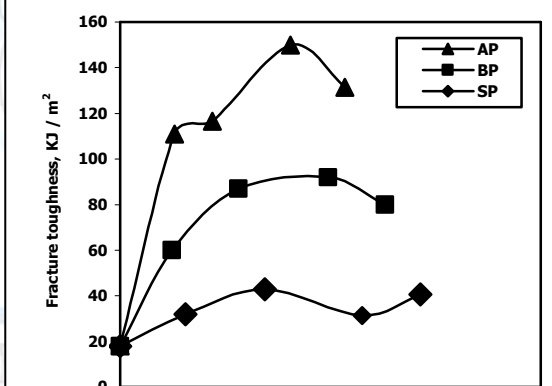

Fig. 8: Influence of powder fillers volume fraction on the fracture toughness of novolac.

5. Conclusions

1-Reinforcing of phenolic resin by fibers as well as powder fillers has improved the mechanical, properties of composites depending on kind and percentage of additives.

2- Tensile strength is increased with increment of volume fraction of fibers as well as powder fillers. BRFC group had high values with respect to fibers composites, and for BPC group with respect to powder fillers composites.

3- The composites have been broken through shearing fracture mechanism with brittle fracture kind, and there are two kinds of bonding between the matrix and additives; weak-bond and strong-bond, through pull-out mechanism with respect to fibers composites and rapture mechanism with respect to powder fillers composites.

4-Results of compression strength have been increased with increment of volume fraction of fibers as well as powder fillers. BRFC group with respect to fibers composites and BPC group with respect to powder fillers composites had high values of compression strength.

5- From the compression results, it can be shown that the failure took place through two kinds of mechanism in different positions at same time; there is failure caused by compressive stresses, which led to buckling phenomena, and failure caused by shearing stresses, which led to shearing cracks.

6- Bending strength is increased with increment of volume fraction of fibers as well as powder fillers. fibers group had high values with respect to powders composites.

7- Fracture toughness has increased with increment of volume fraction of fibers as well as powder fillers. BRFC group with respect to fibers composites and APC group with respect to powder fillers composites had higher values of fracture toughness.

8- From the fracture toughness results, it can be concluded, that the failure takes place by pull-out mechanism with respect to fibers composites, and by pining mechanism with respect to powder fillers composites.

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