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Prediction of Tensile Strength of Nano-short-fiber-reinforced Rubber Composites

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Abstract. The tensile strength of nano-short-fiber-reinforced rubber composites (NFRC) was studied. A new model for predicting the tensile strength of NFRC was put forward based on the mixture law. The influences of the volume content and mechanical performances of main components, short fiber critical aspect ratio, short fiber length and orientation distributions on the tensile strength of composites were investigated. The tensile strengths predicted by the model in this paper are in good agreement with experimental data. Furthermore, the mechanism of tensile fracture of SFRE was discussed. It is found that the tensile fracture of the composites depends largely on the bonding strength of fiber-matrix interface and the length of reinforcing short fibers.

1 Introduction

Nano-short-fiber-reinforced rubber composites (NFRC) is a kind of new composites with dual characteristics of nano-composites and short-fiber-reinforced composites. It is widely used in many fields, such as tyre industry, sealing material industry, damping materials industry, and so on. Its tensile strength is one of important technical indexes for evaluating combination property of sealing composites. The tensile strength of NFRC depends largely on the volume content and mechanical performances of the main components and microstructural parameters, such as short fiber critical aspect ratio, fiber length and orientation distributions. Many researches were carried out on short-fiber-reinforced metal and polymer matrix composites [1-3]. However, the work in rubber composites was rarely reported[4-6]. In this paper, a new mixture law was put forward, the tensile strength of NFRC was predicted, and the influences of the mechanical performances of the main components and microstructural parameters on the tensile strength of composites were also investigated. Furthermore, the mechanism of tensile fracture of NFRC was discussed.

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2 Model for Predicting Tensile Strength

2.1 Fiber Length Distribution

During the manufacturing process of the composites, the shear stresses exerted will break the fibers and result finally in a fiber length distribution with a specific law. The strength of NFRC is undoubtedly related to this distribution, so it is necessary to investigate this distribution. The fiber length distribution can be described with a probability density function. Let us define the fiber length probability density function, $f(l)$. Then the mean fiber length $\bar{l}$ (i.e. the number average fiber length) is derived as follows:

$$\bar{l} = \int_0^{l_{\max}} l f(l) dl \text{ and } \int_0^{l_{\max}} f(l) dl = 1$$

2.2 Fiber Orientation Distribution

During the manufacturing process of the composites, progressive and continuous changes in fiber orientation take place. The changes are related in a complex way to the size and concentration of fibers, the flow behavior of rubber and the processing conditions. An orientation distribution can generally be described with a detailed function, and this distribution affect the strength of NFRC undoubtedly. So let us define the fiber orientation probability density function, $f(\theta)$, too. Then the mean fiber orientation $\bar{\theta}$ (i.e. the number average fiber orientation) is derived as follows:

$$\bar{\theta} = \int_0^{\theta_{\max}} \theta f(\theta) d\theta \text{ and } \int_{\theta_{\min}}^{\theta_{\max}} f(\theta) d\theta = 1$$

2.3 Tensile Strength

The tensile strength of composites is interrelated with its fracture mechanism. It is difficult to predict the tensile strengths of short-fiber-reinforced composites because of different fracture mechanisms of composites whose components and microstructural parameters are quite different. Whereas the tensile strength of short-fiber-reinforced composites can still be predicted simply by a rule of mixtures as follow:

$$\sigma_{cs} = \overline{\sigma_f} V_f + \overline{\sigma_m}(1 - V_f)$$

where σ_{cs} is the tensile strength of the composites， V_f is the volume content of the fiber， $\overline{\sigma_f}$ and $\overline{\sigma_m}$ are the mean stresses of the fiber and matrix when the fracture of composites takes place, and the forms of $\overline{\sigma_f}$ and $\overline{\sigma_m}$ are quiet different in different papers. While Eqs.3 is proposed mainly based on metal and polymer matrix composites, and it is not quiet suitable for predicting the tensile strength of NFRC because the components and microstructural parameters of them are quite different. So a new mixture law is given to predict the tensile strength of NFRC in this paper as:

$$\sigma_{cs} = f_\theta f_i f_f V_f \overline{\sigma_f} + f_d (1 - V_f) \overline{\sigma_m}$$

where

$$\overline{\sigma_m} = E_m \varepsilon_{cu}$$

where f_θ, f_i, f_f and f_d are the modified coefficient of fiber orientation, the modified coefficient of interface, the modified coefficient of fiber interference and dilution effect coefficient. E_m , ε_{cu} are the module and tensile strain of matrix when the fracture of composites takes place. Then we discuss these coefficients detailedly.

If fiber orientation has a distribution law, f_θ can be expressed as:

$$f_\theta = \int_{\theta \min}^{\theta_{\max}} f(\theta)\cos^2\theta d\theta$$

When all fibers are aligned parallel to the loading direction, $f_\theta = 1$; fiber orientation distribution is a random distribution, $f_\theta = 0.5$; all fibers lie perpendicular to the loading direction, $f_\theta = 0$.

When the composites is manufactured, a discontinuous and faulty interface between the fiber and matrix always can be formed, which weakens the reinforcement of fiber and reduces the tensile strength of composites further, but this discontinuous and faulty interface is not agreement with the assumption that interface is continuous and perfect in theory. So we propose to use the coefficient f_i to modify the mixture law. But it is quite difficult to study influence of f_i on the tensile strength of composites from the mechanism as that of f_θ on the tensile strength of composites, so f_i is usually regressed by experiments.

It is a common phenomenon that fibers are connected, contacted and extruded each other, especially when the content of fibers is high. The tensile strength will be reduced when this phenomenon takes place. So we propose to use the coefficient f_f to modify the mixture law according to the method proposed by Karam, and f_f is given as:

$$f_f = (1 - V_f^2)$$

Considering many defects and microcracks in the matrix induced by fibers, which reduce the tensile strength of matrix and induce the early failure of composites, so we use the coefficient f_d to

modify the mixture law, and f_d can be expressed as:

$$f_d = (1 - V_f)$$

Furthermore, we investigate influence of the aspect ratio l/d of the short fiber on the tensile strength of compsites. If the aspect ratio l/d of the short fiber is less than its critical aspect ratio l_c/d , then the short fibers will debond fully and pull out against the shear stress τ_i of interface at the failure of composites. Otherwise, the short fibers will break. So Eqs.4 can be rewritten as:

$$\sigma_{cs} = f_\theta f_i f_f V_f \left(\int_{l_{\min}}^{l_c} f(l)(l/d)\tau_{is} dl + \int_{l_c}^{l_{\max}} f(l)(1 - l_c/2l)\sigma_{fu} dl \right) + f_d(1 - V_f)\overline{\sigma_m}$$

Where

$$l_c / d = \sigma_{fu} / 2\tau_{is}$$

where σ_{fu} is the tensile strength of fiber.

If the fiber aspect ratio is no larger than the fiber critical aspect ratio, the tensile fracture of SEREs is resulted from the interface failure and the fiber debond, and then Eq.(3) can be rewritten as Eq.(11); otherwise, the tensile fracture of composites is mainly induced by the fiber break, and Eq.(1) can be given as Eq.(12).

$$\sigma_{cs} = f_\theta f_i f_f V_f (\bar{l}/d)\tau_{is} + f_d (1-V_f)\overline{\sigma_m} \qquad (l/d \le l_c/d)$$

$$\sigma_{cs} = f_\theta f_i f_f (1-\bar{l}/2l_c) V_f \sigma_{fu} + f_d (1-V_f)\overline{\sigma_m} \qquad (l/d > l_c/d)$$

3 Experiment

3.1 Specimen preparation

The specimens were made of NFRC prepared by the molding process (Tang[5]). Acrylonitrile-butadiene rubber was used as rubber material, and Kevlar aramid fiber with three different lengths (2.5~3.5mm, 4.5~5.5mm and 6.5~7.5mm) as reinforcing fiber. The detail prescription of SFRE is:

NBR:100, Kevlar aramid fiber:5~150, white carbon black:20, vulcanizing agent:2.5, accelerating agent:1, anti-aging agent:2.5, ZnO:5, stearic acid:5.

3.2 Testing

The fiber length and orientation distributions were statistically analyzed by microscope, and the modules and tensile strengths of fiber and rubber. The shear strength of interface and the tensile strength of NFRC were tested on a universal tensile tester at a constant tensile speed of 200 mm/min. The tensile fracture surfaces of NFRC were investigated by scanning electronic microscope.

4 Results and Discussion

Fig.1 exhibits the effects of fiber length and fiber content on the tensile strength of short Kevlar aramid fiber reinforced rubber matrix composites. It can be seen that the tensile strength of composites increases along with the increase of fiber length and fiber content. The results predicted by the presented mixture law are in good agreement with experimental data, but the former is a little larger than the latter. The discrepancy between them is mainly caused by the fiber bending and the disorder of fiber orientations. The fiber bending reduces its reinforced effect and induces the early failure of composites. The disorder of fiber orientations reduces the load subjected by fibers, induces stress concentration round the fibers and results in the tensile fracture of the composites eventually.

It is well known that the tensile fracture mechanism of composites reinforced with short fibers is very complicated and it is related to many mechanical and microstructural parameters, matrix composites. Because the matrix of NFRC is a kind of material with high elasticity, it will not be destroyed even though subjected to a larger strain. However, the NFRC usually have a small tensile strain when destroyed, so the tensile fracture of NFRC is induced not by matrix cracking but by fiberbreak or fiber-matrix interface failure. When the fiber length is long and the bonding strength of the interface is high enough, most of load is transferred to the fiber by the interface, and therefore the fiber is easily to be broken. As a result, the tensile fracture of NFRC takes place. Otherwise, the tensile fracture of NFRC is mainly resulted from the interface failure between the fiber and the matrix. Therefore, it is concluded that the tensile strength of the NFRC depends largely on the bonding strength of the interface and the fiber length.

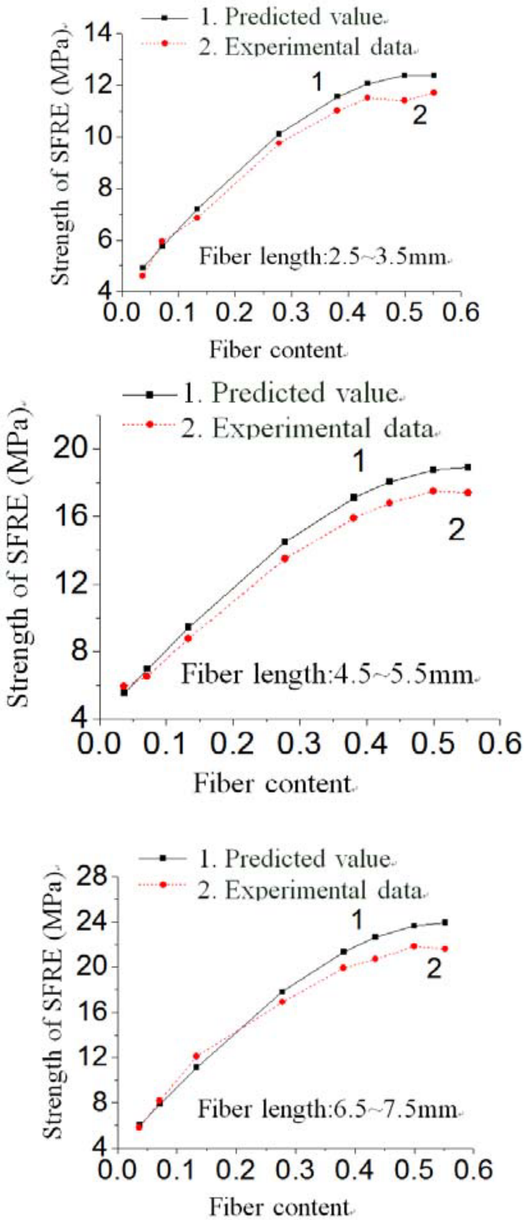

Fig. 1 Theoretical predictions and experimental results of tensile strength of NFRC

5 Summary

The tensile strength of NFRC depends largely on the volume content and mechanical performances of main components, and many microstructural parameters, such as fiber critical aspect ratio, fiber length and orientation distributions and so on. The tensile fracture of the NFRC is mainly related to the fiber length and the bonding strength of the interface between the fiber and the matrix. In consideration of the mechanical performances and microstructural parameters of main components as well as the influences of dilution and interference effects of fibers on the tensile strength of NFRC, the mixture law was modified and a model for predicting the tensile strength of the composites was proposed in this paper. The tensile strengths predicted based on the model are in good agreement with the experimental data.

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