Tensile Mechanical Properties and Its Failure Modes of the Basalt Fiber/Epoxy Resin Composite Material

†J.J. He, *J.P. Shi, X.S. Cao, T.L. Han

School of civil engineering and architecture, Xi'an University of Technology China
†Presenting author: hejing_86@126.com
*Corresponding author: shijp@xaut.edu.cn

Abstract

The uniaxial tensile tests of 16 types of basalt fiber / epoxy (BF/EP) composite material, formed by 4 different fiber orientation and 4 different fiber volume fraction, are carried out, with the tensile mechanical properties and its failure modes of the BF/EP composite material analyzed. The results show that the tensile strength, elastic modulus and limit strain of epoxy resin composite material increased significantly after being mixed with basalt fiber. With increasing fiber orientation angle, the tensile strength, elastic modulus and limit strain of BF/EP composite material decreased with the addition of a certain amount of fiber. However, with increasing fiber volume fraction, the tensile strength, elastic modulus and limit strain of BF/EP composite material increased for certain fiber orientation angle. There is a certain degree of agglomeration phenomenon in epoxy resin when mixed with basalt fiber with more than 1.2% of volume fraction.

Keywords: Basalt fiber; Epoxy resin; Composite material; Failure mode

Introduction

Basalt fiber is a new type of mineral fiber made from the melting of natural basalt in high temperature（1400~1500℃）[1]. Because of its characteristics such as high elastic modulus and tensile strength, it is widely applied in areas including machine building industry, aviation industry and building materials industry[2, 3，4, 5]. Basalt Fiber reinforced epoxy resin is made from a certain addition (volume mixing rate) of basalt fiber into epoxy resin. With the addition of basalt fiber, internal stress of small epoxy resin (matrix) and mechanical properties of epoxy resin can be effectively reduced [6].

At present, researches on Basalt Fiber reinforced epoxy resin are focused on the influence of fiber surface modification on mechanical properties [7, 8], yet there are fewer researches of the influence of fiber distribution on tensile properties of BF/EP composite material. However, fiber distribution can exert a significant influence on mechanical properties of BF/EP composite material [9,10,11].

As the main parameter reflecting fiber in matrix, fiber orientation is an important factor influencing mechanical properties of BF/EP composite material [12、13]. Therefore, some scholars made attempts to use flow field orientation （internal fluid viscous force）before matrix curing to control fiber orientation. For example, Yang Binxin and other scholars [14] conducted researches on flow field formed in the interval of two concentric rotating cylinders and the fiber movement and orientation in the flow field. The result shows that fiber has its movement and orientation along flow field. With the use of numerical algorithm of finite volume method and finite difference method, Zhang [15] analyzed the flowing behavior of fiber reinforced polymer melt in contraction flow chamber. The result shows that when shearing motion dominates, fiber has the orientation of cyclonic rotation; when stretching exercise dominates, fiber has the stretching orientation along monopodium.

In the thesis, with the use of handmade chute device, composite materials of oriented basalt fiber/epoxy resin composite material of different mixing rate are produced. After the completion of matrix solidification, along the fiber orientation, experiments are conducted concerning its axial tensile properties and destroying morphological analysis of its samples, with the cutting included angles of 0° ,15° ,30° and 45° of tensile samples. The thesis is to make people know the influence of fiber orientation and mixing rate on tensile properties of BF/EP composite material and to provide some experimental bases for the design and engineering application of BF/EP composite material.

Experiments and Researches of Tensile Properties of BF/EP composite material

Material Parameter & Raw Materials

Curing agent uses polyamide, and diluent uses acetone. Matrix is compounded according to mass ratio of M_1(epoxy resin): M_2(curing agent): M_3(diluent)=38:25:1. It is tested that after solidification, the tensile intensity of matrix is 16.67 MPa, limit strain 0.002, shearing strength 21.73MPa and curing residual stress 0.31 MPa. The fiber is Chopped discontinuous basalt fiber, and physical and mechanical indexes of basalt fiber are shown in sheet1.

Table. 1 Physical and mechanical indexes of basalt fiber

Density (g/cm^3)	Tensile strength (MPa)	Limit elongation (%)	Tensile modulus (GPa)	Diameter (mm)	Length (mm)
2.65	3300	3.2	100	0.01	12

The Design and Technology of BF/EP composite material

The volume addition *i* of basalt fiber range between 0.6%, 0.9%, 1.2% and 1.5%. The orientation angle θ of fiber in matrix ranges between 0° , 15° , 30° and 45° . The size of samples is 10mm×20mm×300mm and 3samples is one group.

To mix epoxy resin, curing agent and diluent according to a certain proportion, matrix of epoxy resin can be formed, which is added by basalt fiber of a certain addition and then pour it into a chute. Because of gravity, basalt fiber will flow into test mode through chute and elongation flow field of matrix will be formed which will lead to the fiber orientation approaching tensile direction[16、17]. Through the control of include angles between chute and surface, different gravity flow fields are formed. When mixing rate of fiber is 0.6%, 0.9%, 1.2% and 1.5% and included angle of chute is 15° , 23° , 30° and 45° , the fiber orientation in matrixes are relatively consistent. After the solidification of its matrix (about 48hours, 20±2℃）, along the direction of fiber orientation, design sizes are cut in the angles of 0°, 15°, 30°and 45°. Therefore, 4types of fiber orientation and 4 different fiber volume fractions under 16 kinds of BF/EP composite material are gained.

Analysis of the Experiment Result

Uniaxial tensile test is conducted by adopting WAW-1000 universal testing machine and stress-strain curves are collected in the loading rate of 5N/s. The tensile stress-strain curves of different fiber orientation are given in fig. 1a、b、c、d when the volume additions of fiber are 0.6%, 0.9%, 1.2% and 1.5%.According to fig.1a, when *i* is 0.6% and θ is 0° ,15° and 30° , the tensile strength of fiber to matrix has increased 16%, 8% and 1%, and limit strain of fiber to matrix has increased 22%, 5% and 1%. According to fig. 1b, when *i* is 0.9% and θ is 0°,15°, 30° and 45° , the tensile strength of fiber to matrix has increased 45%, 36%, 22% and 12%, and limiting strain of fiber to matrix has increased 29%, 22%, 8% and 4%. According to fig. 1c, when i is 1.2% and θ is 0°,15°, 30° and 45°, the tensile strength of fiber to matrix has increased 90%, 81%, 56% and 34%, and limiting strain of fiber to matrix has increased 88%, 54%, 35% and 20%. According to fig. 1d, when i is 1.5% and θ is 0°,15°, 30° and 45°, the tensile strength of fiber to matrix has increased 106%, 98%, 80% and 58%, and limit strain of fiber to matrix has increased 114%, 75%, 38% and 21%. Therefore, the addition of basalt fiber has different improving impacts on the tensile strength and limiting strain of fiber and will increase as the mixing rate becomes higher; with increasing fiber orientation angle, the tensile strength and limit strain of the complex decreased with the addition of a certain amount of fiber.

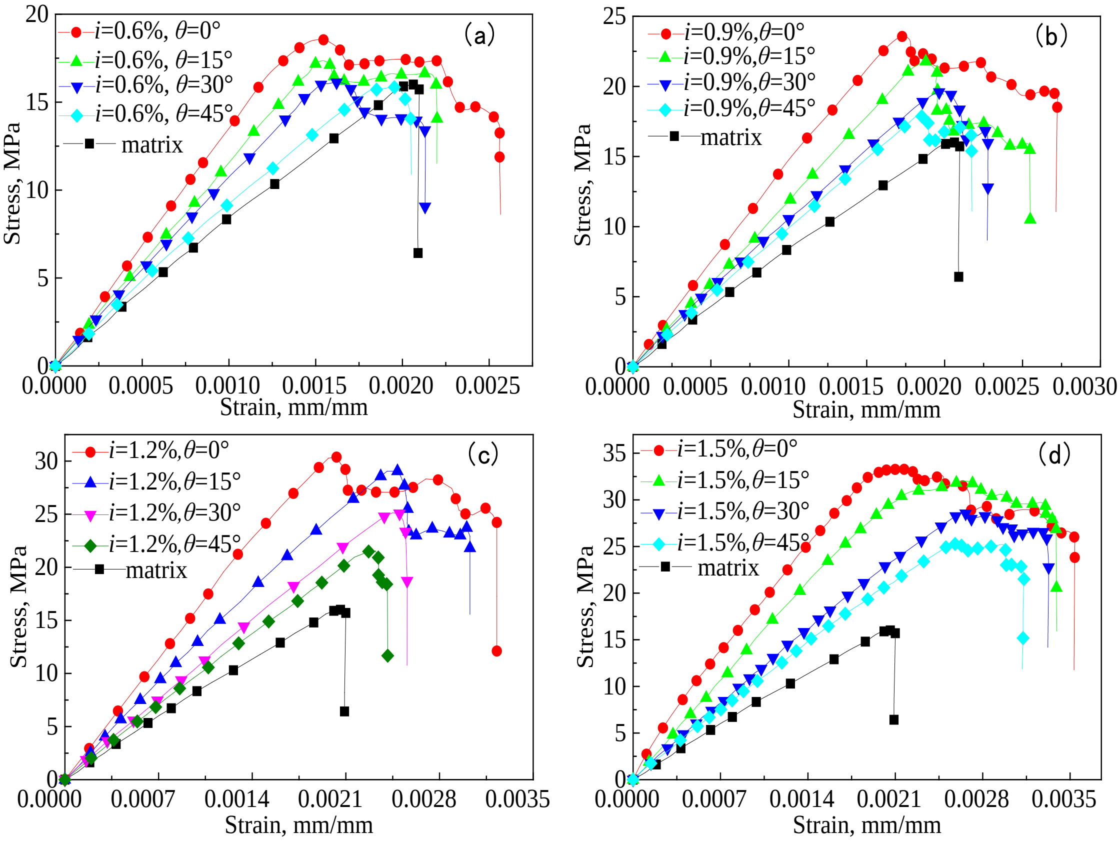

Fig.2 Tensile stress-strain curve of BF/EP composite material with different orientation and different volume mixing rate of fibers

In conclusion, the tensile strength and limit strain of BF/EP composite material have some relation with decreased with the orientation and volume mixing rate of fiber. In order to have further analysis of the influence of the orientation and volume mixing rate of fiber on tensile properties of BF/EP composite material, enhancement coefficients β is introduced, which is

$$\beta = \frac{I_f}{I_m} \tag{1}$$

In it, If is the tensile property indicator of BF/EP composite material, such as its tensile strength σ_f、 elastic modulus E_f, and limit strain ε_f; Im is the tensile property indicator of matrix, such as its tensile strength σ_m, elastic modulus E_m and limit strain ε_m; therefore, it can be got from fig.1 the enhancement coefficient of tensile strength β_t, the enhancement coefficient of elastic modulus β_e, the enhancement coefficient of limit strain β_s in different orientation and volume mixing rate of fiber . Fig. 3a, b, c are showing quadric surface fitting of β_s, β_e, β_t changing with fiber volume ratio i and orientation angle θ, whose fitting surface function are

$$\beta_s = 1.274 - 0.3661i - 0.008179\theta + 0.4552i^2 - 0.00007442i\theta + 0.00004652\theta^2 \tag{2}$$

$$\beta_e = 1.469 + 0.05436i - 0.008847\theta + 0.2491i^2 - 0.01271i\theta + 0.000182\theta^2 \tag{3}$$

$$\beta_t = 0.3937 + 1.301i + 0.003205\theta - 0.08973i^2 - 0.008662i\theta - 0.000064437\theta^2 \tag{4}$$

Correlation coefficients of formula (2), (3) and (4) are 0.9677, 0.9783 and 0.9791. It can be known that surfaces of fig. 3a, b and c have objective laws representing β_s、β_e、β_t changing with i、θ. It can be known from fig. 3a, b, and c that a certain addition of basalt fiber can have a significant improvement on the tensile strength, elastic modulus and limit strain of epoxy resin composite material ; With increasing fiber orientation angle, the tensile strength, elastic modulus and limit strain of BF/EP composite material decreased with the addition of a certain amount of fiber. However, with increasing fiber volume fraction, the tensile strength, elastic modulus and limit strain of BF/EP composite material increased for certain fiber orientation angle.

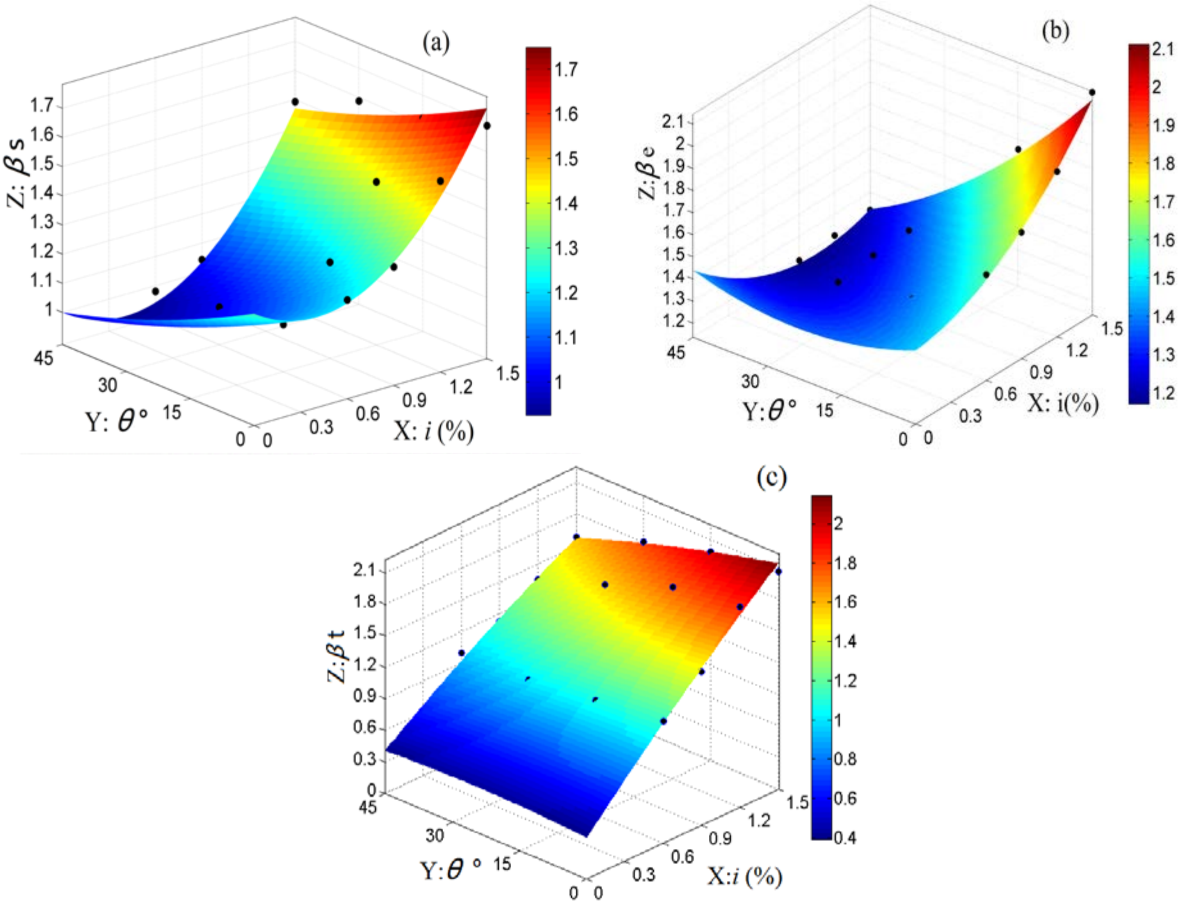

Fig.3 The fitting surface of fiber reinforcement coefficient with fiber orientation angle and fiber addition rate

Analysis of BF/EP composite material Tensile Failure Mode

To analyze the tensile failure mode of samples and to observe the facture surface of samples through SEM technology, it can be found that there is a certain degree of agglomeration phenomenon in epoxy resin when mixed with basalt fiber with more than 1.2% of volume fraction. Fig. 4 gives e-sports scan results of BF/EP composite material sample fracture surface. Fig. 4a and 4b show agglomeration phenomenon of fiber in fracture surface when fiber volume mixing rates are 1.2% and 1.5%. It is because fiber and matrix enjoy different mixing technology, and it makes fiber hard to distribute evenly in epoxy resin and only to presenting in group or bundle [18].

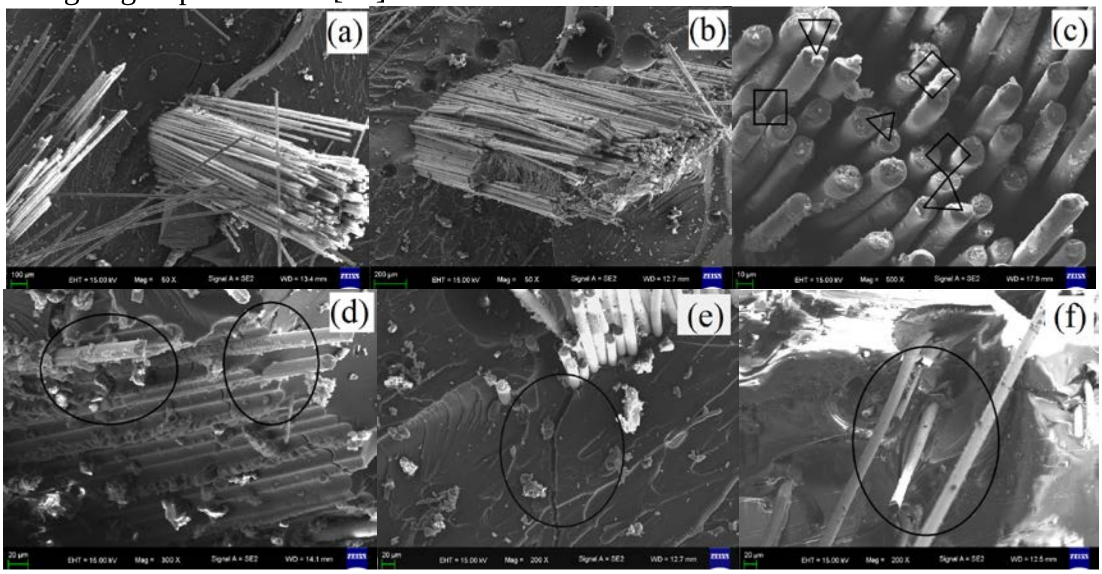

Fig.4 e-sports scan results of BF/EP composite material sample fracture surface

This kind of fiber agglomeration can be called "fiber-group effect". It can be known that because of fiber-group effect, firstly, in and between fibers, there is only small gap, which makes it hard for matrix to enter fiber agglomerates and there is crevice in and between fiber agglomerates, seeing fig. 4c. Fibers in fiber agglomerates losing bound with matrix, most of its failure mode presents as the fiber pulling-out, while peripheral fiber of fiber agglomerates bounding well with matrix, most of its failure mode presents as the fiber pulling-off, seeing fig.4. According to Tsai Theory [19,20], matrix cracks for its tensile strength under tense force and all its load is transferred to fiber to its pull-off. Fiber approaches its yield strength and destroys with matrix, and the compounding strength of fiber and matrix is greater than its tensile strength among which fiber plays an enhanced role in matrix. However, matrix is destroyed before the pull-out fiber getting to its yield limitation, and the bonding strength of fiber and matrix is smaller than its tensile strength among which fiber doesn't play an enhanced role in matrix. Similarly, crevice in fiber group leads to matrix cracking in advance to some degree and the tensile strength of composite decreasing, seeing fig.4e. Compared with sample fracture surface of fiber group, the fracture surface of samples is rough and has big bumps when fiber has even distribution, see fig.4f. It is because when fiber distributes evenly, it bonds well with matrix, distracting stresses concentration phenomenon within matrix and changing the stress path of matrix cracking, thus leading to the greater roughness of fracture surface. Researches show that tensile strength of solid material has some relation with its 3-dimension roughness of its fracture surface[21、22]. In conclusion, fiber-group effect has reduced the utilization of fiber to some degree and the improvement effect of fiber to matrix tensile strength. So in the design and engineering application of BF/EP composite material, attempts should be made to decrease and avoid fiber-group phenomenon.

Conclusion

The thesis analyzes different fiber orientation and BF/EP composite material tensile strength experiments and researches as well as failure mode of different fiber volume mixing rate, it can be concluded:

(1) With a certain amount of basalt fiber, the tensile strength, elastic modulus and limit strain of epoxy resin composite material have significant improvement effect. With increasing fiber orientation angle, the tensile strength, elastic modulus and limit strain of BF/EP composite material decreased with the addition of a certain amount of fiber. However, with increasing fiber volume fraction, the tensile strength, elastic modulus and limit strain of BF/EP composite material increased for certain fiber orientation angle.

(2) The internal fiber of the group cannot bond completely with the matrix for "fiber group-effect", and the tensile failure modes of BF/EP composite material are fiber pull-out and fiber pull-off. When the pulled-off fiber researched its yield limit, the BF/EP composite material failed. These situations are more associated with peripheral fiber of the group and non-group fiber. However, failure of the BF/EP composite material happened even when the pulled-out fiber did not research its yield limit. These situations are associated with internal fiber of the group.

References:

[1] Colombo, C., Vergani, L., & Burman, M. (2012) Static and fatigue characterisation of new basalt fibre reinforced composites, *Composite Structures* **94**, 1165−1174.

[2] Fiore, V., Bella, G. D., & Valenza, A. (2010) Glass–basalt/epoxy hybrid composites for marine applications. *Materials & Design* **32**, 2091−2099.

[3] Wei B, Cao H, Song S. (2010) Tensile behavior contrast of basalt and glass fibers after chemical treatment[J]. *Materials & Design* **31**,4244−4250.

[4] Lopresto, V., Leone, C., & Iorio, I. D. (2011) Mechanical characterisation of basalt fibre reinforced plastic. *Composites Part B Engineering* **42**, 717-723.

[5] Todic, A., Nedeljkovic, B., Cikara, D., & Ristovic, I. (2011) Particulate basalt–polymer composites characteristics investigation, *Materials & Design* **32**, 1677−1683.

[6] Kim, M. T., Kim, M. H., Rhee, K. Y., & Park, S. J. (2011) Study on an oxygen plasma treatment of a basalt fiber and its effect on the interlaminar fracture property of basalt/epoxy woven composites, *Composites Part B Engineering* **42**, 499−504.

[7] Lee, J. H., Rhee, K. Y., & Park, S. J. (2010) The tensile and thermal properties of modified cnt-reinforced basalt/epoxy composites, *Materials Science & Engineering A* **527**, 6838−6843.

[8] Huonnic, N., Abdelghani, M., Mertiny, P., & Mcdonald, A. (2010) Deposition and characterization of flame-sprayed aluminum on cured glass and basalt fiber-reinforced epoxy tubes, *Surface & Coatings Technology* **205**, 867−873.

[9] Fletcher, A. J., & Oakeshott, J. L. (1994) Thermal residual micro stress generation during the processing of unidirectional carbon fibre/epoxy resin composites: random fibre arrays, *Composites* **25**, 806−813.

[10] Hobbiebrunken, T., Hojo, M., Jin, K. K., & Ha, S. K. (2008) Influence of non-uniform fiber arrangement on microscopic stress and failure initiation in thermally and transversely loaded CF/epoxy laminated composites, *Composites Science & Technology* **68**, 3107−3113.

[11] Yang, C., Huang, H. X.,& Li, K. (2010) Investigation of fiber orientation states in injection-compression molded short-fiber-reinforced thermoplastics, *Polymer Composites* **31**, 1899–1908.

[12] Pochiraju, K., & Jovanović, V. (2005). Modeling material property heterogeneity in fiber-reinforced injection molded plastic parts. *Polymer Composites*, **26**(1), 98-113.

[13] Gui, L. L., Zhou, H. W., & Wang, H. W. (2011). Theoretical analysis of young's modulus for unidirectional fiber reinforced composites with different fiber orientations. *Advanced Materials Research,* **216**, 773-776.

[14] Yang Bin-Xin, Ouyang Jie, Zhou Wen, Wang Fang & Li Xue-Juan. (2015). Dynamic simulation of fiber orientation in the gap flow field between two rotating cylinders. *Acta Phys. Sin*. **64**(11), 404-413.

[15] Zhang, H., & Jie, O. (2007). Fiber orientation and stress analysis for fiber reinforced polymeric melt. *Acta Materiae Compositae Sinica*, **24**(6), 153-159.

[16] Ye, Z., Lee, D., Campbell, S. A., & Cui, T. (2011). Thermally enhanced single-walled carbon nanotube microfluidic alignment. Microelectronic Engineering, **88**(9), 2919-2923.

[17] Chandrasekaran, V. C. S., Advani, S. G., & Santare, M. H. (2010). Role of processing on interlaminar shear strength enhancement of epoxy/glass fiber/multi-walled carbon nanotube hybrid composites. Carbon, **48**(13), 3692-3699.

[18] Yang, C., Huang, H. X.,& Li, K. (2010) Investigation of fiber orientation states in injection-compression molded short-fiber-reinforced thermoplastics, *Polymer Composites* **31**, 1899–1908.

[19] Tsai, S. W., & Wu, E. M. (1971) A general theory of strength for anisotropic materials, *Journal of Composite Materials* **5**, 58−80.

[20] Liu, K. S., & Tsai, S. W. (1998) A progressive quadratic failure criterion for a laminate 1, *Composites Science & Technology* **58**, 1023-1032.

[21] Trefilov, V. I., Kartuzov, V. V., & Minakov, N. V. (2001). Fractal dimension of fracture surfaces. *Metal Science and Heat Treatment*, **43**(3), 95-98.
[22] Li, Y., Yan, Q., & Du, X. (2012). Relationship between autogenous shrinkage and tensile strength of cement paste with scm. *Journal of Materials in Civil Engineering*, **24**(10), 431.