EFFECTS OF FIBER DISTRIBUTION AND SHAPE ON TENSILE PROPERTIES OF INJECTION MOLDED COMPOSITE

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SUMMARY: The survival rate(residual fiber length/initial fiber length) decreases with initial fiber length and fiber volume content. During injection molding processes, the degree of damage is higher for carbon fiber than for glass fiber. Also, it is found that the survival rate increases with hyperbolic tangent relationship as nozzle diameter increases. This separates the damage between nozzle diameter and other factors. The higher survival rate is, the stronger material is. Based on the distribution of residual fiber length in experimental works, five different fiber lengths are selected to model the fiber distribution and to predict the tensile properties of short-fiber reinforced composite(SFRC). Compared with the experimental results, the predicted modulus and strength show reasonable agreements. In general, it is found that the interactions between fiber and matrix and the type of fiber distribution and length are the most important factors in the reinforcement of SFRC.

KEYWORDS: Fiber Aspect Ratio, Damage during Injection Molding, Fiber Distribution, Tensile Strength and Modulus, Prediction

INTRODUCTION

Short-fiber reinforced composites(SFRC) have been used for years for various applications due to their ease of fabrication, economy and reasonable mechanical properties. However, the potential of the SFRC has not been fully realized because many factors and complex phenomena involved in the SFRC strength have not been fully understood. It is believed that the strength of SFRC can be further improved by controlling key factors contributing to the strength of the composites[1.2]. Among the factors, the fiber length and its distribution are believed to be the most important ones in the reinforcement of SFRC[3.4].

The fiber damage takes place during injection molding of SFRC due to fiber-polymer interaction, fiber-fiber interactions, and fiber contact with surfaces of the processing equipment. In general, it is known that the residual fiber length decreases with increasing in fiber content[4,5] and then reduces fiber reinforcing efficiency[6].

Among other factors affecting the properties of SFRC, few of the key elements having profound effects on the properties are the volume, modulus and geometry of the reinforcing materials. The geometry of reinforcing material can be described as shape, size, aspect ratio(l/d) and distributions[4]. Many micromechanical models show a good agreement in low fiber volume fraction(V_f) with experimental data but a poor agreement as V_f increases. The reason is believed to be an interaction between neighboring fibers that can be negligible in low V_f. Therefore, the model with multi-fiber composite is more desirable to study even though it is an expanded type of special unit cell model with a periodic array of fibers. Tvergaard[1] shows a decreasing of flow stress and strain hardening in the case of staggered array when a periodic array of aligned and staggered short fibers is used by employing an axisymmetric unit cell model to study the effects of reinforcing arrangement.

The objective of this study is to investigate the effects of injection molding conditions and fiber volume on the survival rate of fiber based on fiber length and its influence on tensile modulus(E_c) and strength of SFRC. Based on the residual fiber length, finite element analysis is performed to understand the effects of aspect ratio(l/d), fiber distribution pattern, fiber length and V_f on mechanical properties using 2-D multi-fiber composite model.

EXPERIMENTAL: MATERIALS, PROCESSING AND TESTING

The materials used for this study were commercially available neat Polypropylene purchased from SK Co., Ltd. and carbon(TZ-507) and glass(E-glass) fibers from Hankook Fibers Co. Table 1 shows the material properties of used materials. To maintain the initial fiber length, the compounding with any machines is not applied. Instead, The pre-mixing of dried PP resin and the chopped fibers is performed by hand with nominal 3, 5 and 7 vol. % with care. The used fiber lengths are 1 mm, 3 mm and 6 mm. The tensile specimens in accordance with ASTM D638 type I were made by injection molding using LG machine with molding pressure of 8.2~9.8 MPa and molding temperature of 220~200 ^{o}C. These specimens were kept at mold temperature at 20 for 10 sec. After cooling for 5 sec, the specimens were removed from the mold. The nozzle sizes of injection and mold sides are 3, 6 and 9 mm.

All tensile tests for the specimens were performed according to ASTM D638M using a Shimadzu testing machine (model-AG 5000). The tests were performed at a constant cross-head speed of 5 mm/min. For each condition, at least, five specimens were tested and the average results are presented.

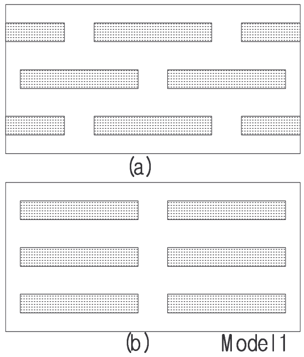
Table 1 : Mechanical properties of carbon fiber, glass fiber and polypropylene

Mechanical Properties	CARBON FIBER (ACELAN TZ-507)	GLASS FIBER	POLYPROPYLENE
Tensile Strength (MPa)	4200	1750	20-35
Tensile Modulus (GPa)	270	70	0.7-1.4
Density (g/㎤)	1.8	2.55	0.9-0.91
Ultimate Elongation (%)	1.5	15-20	10-500
Filament Diameter (㎛)	6.8	13.7	

FINITE ELEMENT ANALYSIS: FIBER VOLUME AND DISTRIBUTION

The 2-D multi-fiber composite model developed from the “Representative Volume Element” concept is used to analyze the mechanical properties of SFRC. The special code system for modeling and meshing has been developed to accept the changing of aspect ratio at given fiber volume fraction for aligned and staggered fiber geometries.

Fig. 1 shows the preliminary 2D multi-fiber composite model representing x-direction as the loading direction along the fibers and y-direction as the cross-section of fibers. There are 3 periodic fiber layers with a constant distance between centers of the neighboring fibers for different fiber volume fractions and aspect ratios. The fiber length is L at the basic aligned and staggered models, and the various models have used 2 different fiber lengths: basic length of L and broken fiber length of 0.45L. The x-direction gab is 0.1L and y-direction gab is kept constant at same volume fraction.



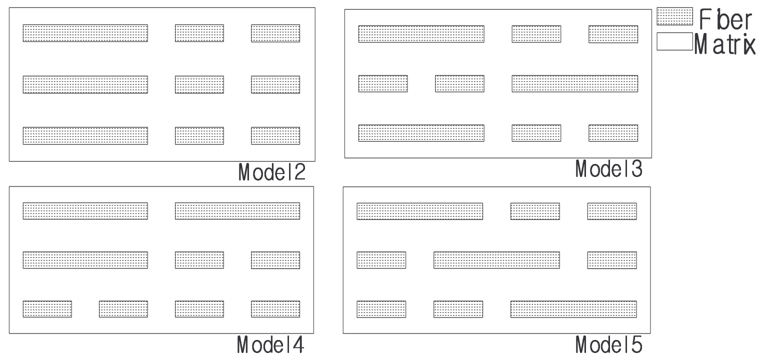


Fig. 1. Staggered array (a) and Aligned array (b) as a basic model

Fig. 2. Types of fiber distribution with different fiber lengths based on aligned array

Based on preliminary study, the expanded models using 5 different fiber lengths are examined as shown in Fig. 3. Table 2 shows the original fiber length and number of fiber used for expanded array model.

Table 2: Number of fiber used for expanded array model.

	0.1L	0.3L	0.45L	0.7L	L
Original fiber length(μm)	103.04	309.1	463.7	721.3	1030.4
Number of fiber	4	8	10	6	1

This expanded model with five different fiber lengths can have 4.2651E12 types of fiber array for analysis. The phase of matrix and fiber is an isotropic material and interface between two components has a perfect bonding. Fiber has a linear elastic behavior up to break and matrix has an elastic-plastic behavior. In this presentation, the effective modulus is measured only in the elastic region. The FE computations are performed using 4 noded isoparametric elements for 2-D model

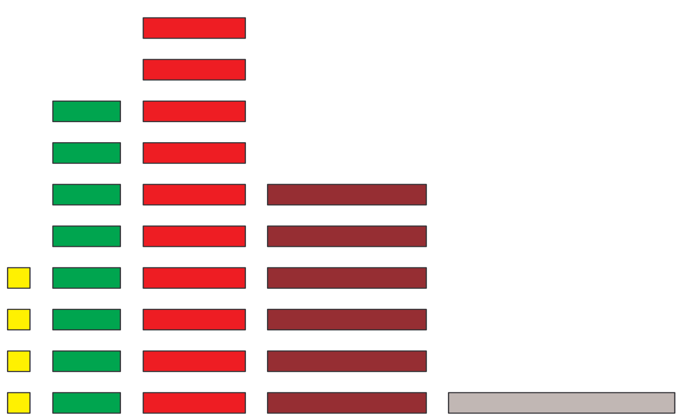


Fig. 3: The chosen fiber lengths for expanded Model

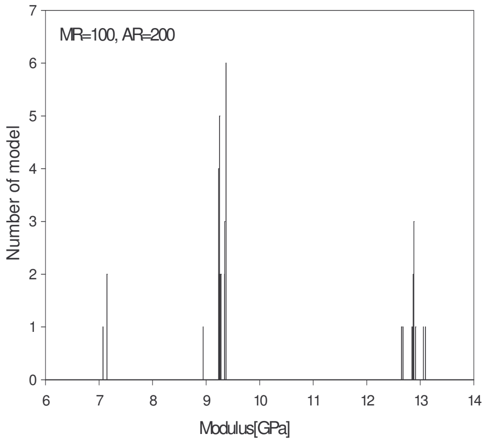


Fig. 4: Number of model depending on the modulus with a given fiber distribution.

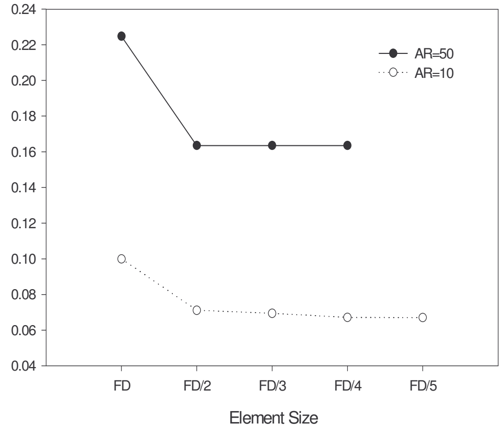


Fig. 5: Comparison of modulus with different mesh sizes

The FE formulations in 2-D Multiple fiber model are under the condition of plane strain with boundary conditions of *dx=0* at x=0 and *dy=0* at y=0 as shown in Fig. 1 and Fig. 2. The displacement controlled computations are performed by the general purpose FE program, ANSYS 5.7. Fig. 4 shows the variation of modulus with 45 models which are the possible combination from Fig. 2 with modulus ratio of 100 and aspect ratio of 200. It represents 손 group of modulus depending on fiber distribution as staggered, aligned and mixture of two. Based on these results, the 11 different models with the maximum, medium and minimum modulus or strength are organized.

To obtain the effective modulus(E_c), the applied far field tensile strain(ε_c) is loaded to 0.5%. The strains are assumed to develop instantaneously, that is independent of time. As a method to increase the aspect ratio, the configuration of basic model is extended in x-axis. It has been confirmed that this extension has no effects on the mechanical properties of model composite. In solution and post-process, the tensile strength of fiber and matrix in composite is compared with strength of fiber and matrix. Until the strengths in composite are more than strengths of material, the incremental search method is applied. In general, it is known that the tensile strength shows a large variation depending on the mesh size. To check this, the mesh size is fixed as half of fiber diameter throughout the analysis. As shown in Fig. 5, the mesh size is smaller than a half fiber diameter. Then, Young's modulus shows a similar value.

And then, using the effective modulus of short-fiber composite, the corresponding strength can be obtained as

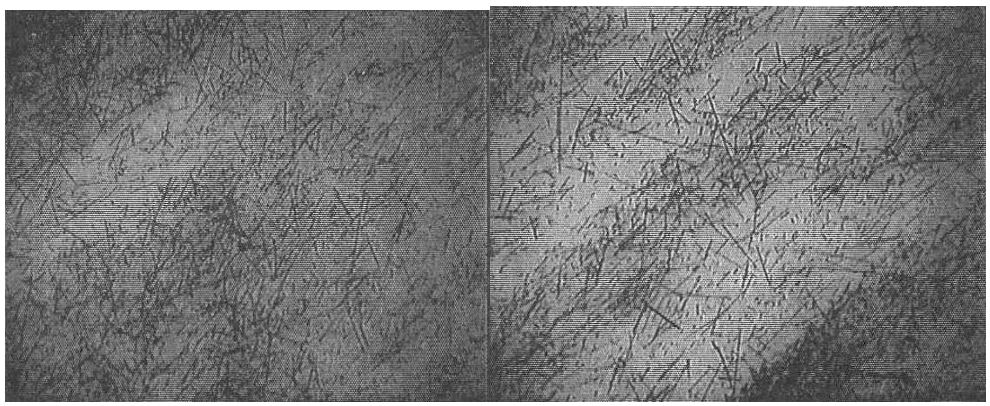
$$[\sigma]_c = \frac{\int_n [\sigma_c]_n dv_n}{\int_n dv_n} \qquad \text{and} \qquad [\sigma]_c = [E]_c [\varepsilon]_c$$

where $[\sigma]_c$ represents the average stress for 2-D multi-fiber model, $[\sigma_c]_n$ represents the stress in n^{th} element, dv_n is the volume of n^{th} element and $[E]_c$ is the effective modulus of short-fiber reinforced composites.

RESULTS AND DISCUSSION

1. Fiber and Survival Rate

Fig. 6 shows the carbon fiber length distribution after pyrolytic decomposition for SFRC with initial fiber length: (a) ℓ_0 =1 mm, (b) ℓ_0= 3 mm



(a) Average ℓ_r = 419.5 μm (b) Average ℓ_r = 463.7 μm

Fig. 6: The carbon fiber length distribution with average fiber length for (a) ℓ_0 =1 mm, and (b) ℓ_0= 3 mm , respectively .

Fig. 7 shows the fiber length distribution pattern of Fig. 6 using Image Pro 3.0.

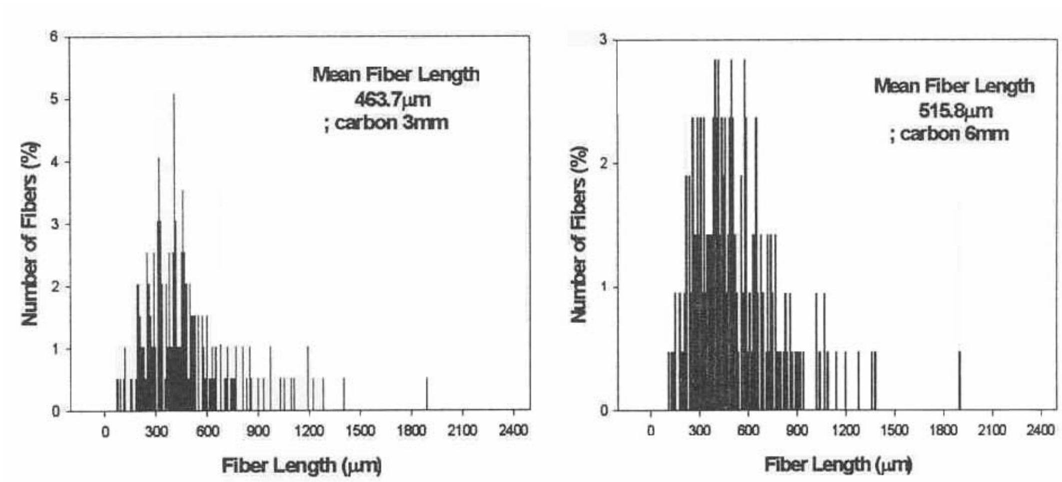


Fig. 7: Fiber length distribution in PP/CF composites after injection molding with original fiber length of 3 and 6mm, respectively

The survival rate(%) as residual fiber length, ℓ_r divided by initial fiber length, ℓ_0, decreases with initial fiber length and fiber volume content as shown in Fig. 8. The degree of damage as slope of this curve is slightly higher for carbon fiber than for glass fiber. Also, it is found that the survival rate(S) increases with hyperbolic tangent pattern as nozzle diameter increases as shown in Fig. 9. This separates the cause of damage between nozzle diameter and other factors. As expected, the higher survival rate, the stronger the material.

Fig. 10 compares the theoretical and finite element results for longitudinal modulus, E_{11} with V_f =30%. The stronger influence of fiber aspect ratio on E_{11} is apparent, and all of theories exhibit a similar S-shape curve, asymptoting to the same rule of mixtures vale at high aspect ratio. Tsai and Pagano[7] have shown that the modulus of SFRC can be predicted approximately using Halpin-Tsai equation of E_{11} and E_{22} as E_c=(3/8) E_{11} + (5/8)E_{22}. Fig. 11 shows the comparison between predicted modulus[7] and measured modulus as functions of aspect ratio and nozzle diameter. As shown, even though the same initial fiber length (AR=440) is used, the residual fiber length is different depending on nozzle diameter(3mm marked as o, 6 mm as x and 9mm as ∇).

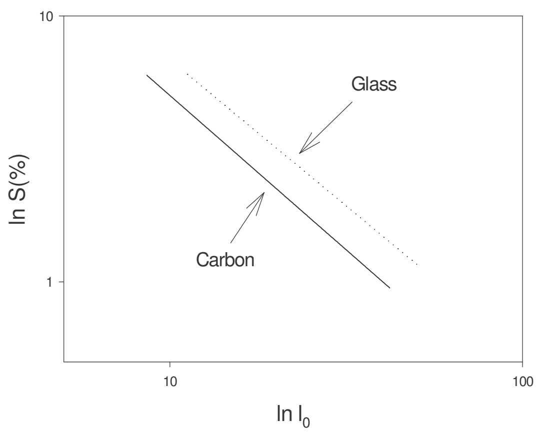


Fig. 8: The survival rate(S) as functions of initial fiber length and fiber type

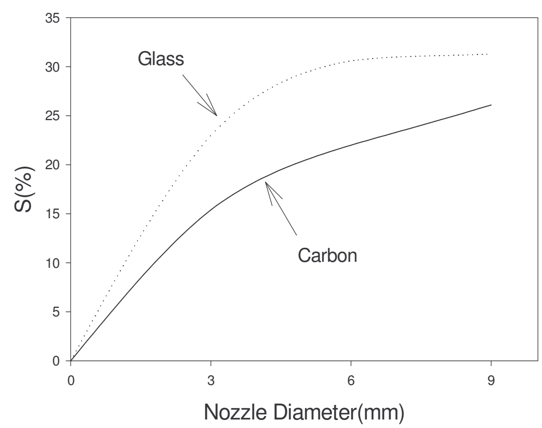


Fig. 9: The survival rate as a function of nozzle diameter.

The data with residual fiber length shows a better fit than the data with initial fiber length.

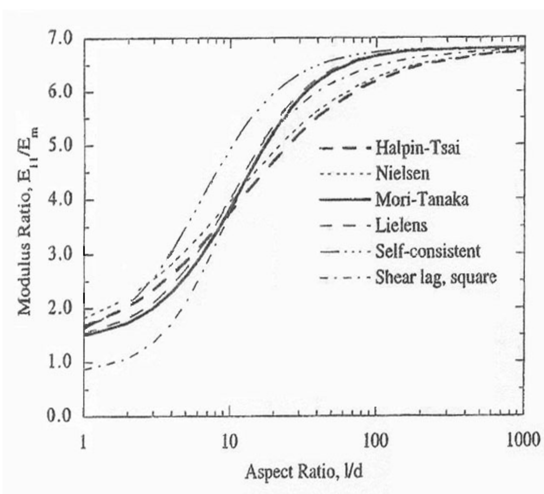


Fig. 10: Theoretical predictions of modulus as a function of aspect ratio.

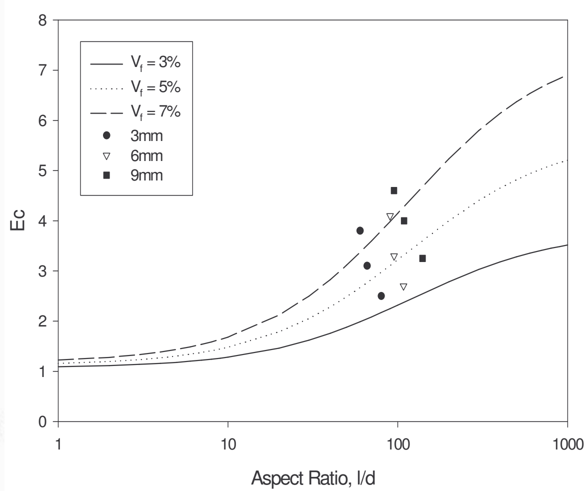


Fig. 11: Comparison of predicted and experimental modulus ratio as functions of aspect ratio and nozzle diameter.

2. Effects of Fiber Volume(V_f) and Fiber Aspect Ratio(AR)

As mentioned before, the fiber length and distribution are believed to be the most important ones in the reinforcement of SFRC. Fig. 12 shows the primary results of effective modulus ratio (E_c/E_m) at MR =100 as function of V_f and aspect ratio for the aligned model. As expected, the effective modulus increases with fiber length and volume fraction. Fig. 13 shows the primary results of E_c/E_m at V_f =30% as a function of aspect ratio for various models that based on the aligned model.

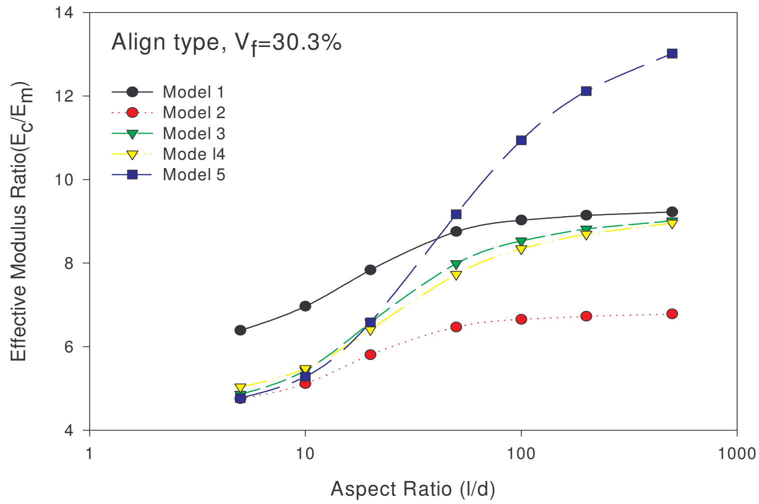


Fig. 12: The effective modulus ratio(E_c/E_m) as a function of aspect ratio compared with the calculated results of Halpin-Tsai.

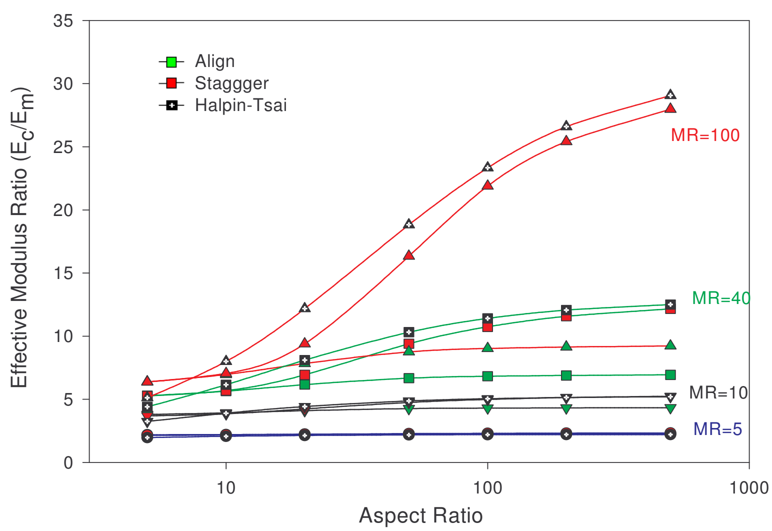


Fig. 13: Comparison of effective modulus ratio (E_c/E_m) of short fiber composites for simple model.

Fig. 10 shows the effects of fiber distribution as staggered and aligned array on the effective modulus ratio(E_c/E_m) as a function of AR and modulus ratio(E_f/E_m) compared with the calculated results of Halpin-Tsai[9]. The results of staggered array are in good agreement with results of Halpin-Tsai prediction. As shown in figure 11, the model 2 has the lowest tensile modulus and even lower than that of basic model with V_f =20%. Since the short fibers aligned perfectly together in certain area, the composite can be deformed more easily. Meanwhile, Model 5 has the highest effective tensile modulus that is even larger than the basic aligned model. As similar to the basic staggered array, there are more interactions among the neighboring fibers that led to high stiffness of composite.

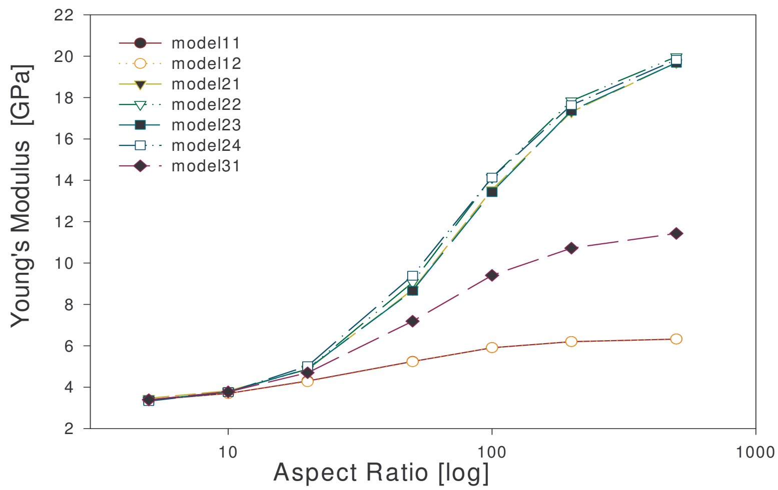


Fig. 14: The predicted Young's modulus with various expanded models as a function of AR.

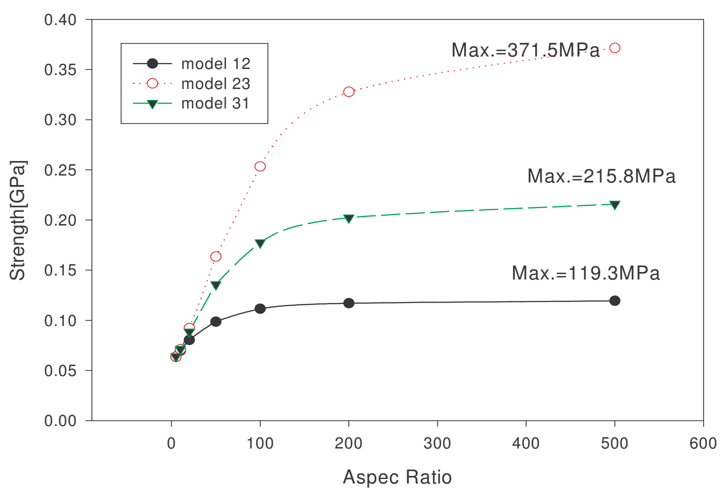


Fig. 15: The predicted strength with selected expanded models as a function of AR.

Fig. 12 shows the lowest modulus for aligned type and the highest modulus for staggered type as expected from the preliminary analysis. The results show 3 times differences in modulus depending on the array types with V_f =30%. This numerical difference will be lower as the fiber volume content decreases. However, considering that the Young's modulus is a stationary property, this difference is a quite noticeable result and shows the possibility to improve stiffness of SFRC by manipulating fiber length and distribution. Compared with experimental data in Fig. 9, the specimen that tested in this work seems to have the fiber distribution pattern with a mixture of staggered and aligned types. The tensile strength also shows the significant difference depending on the fiber distribution pattern and AR with a parabolic relationship. As shown in Fig. 13, the tensile strength increases fast in the AR range of 1 ~ 200 and then approaches a constant value at higher AR. Also, the tensile strength is the highest with staggered array and the lowest with aligned array. However, the increasing rate of tensile strength depending on AR is lower for low V_f. Also, the AR value that approaches the limiting value also increases as the V_f decreases.

CONCLUSION

The survival rate decreases with initial fiber length and fiber volume content. The degree of damage is slightly higher for carbon fiber than for glass fiber during injection molding processes. Also, it is found that the survival rate increases as the nozzle diameter increases. As expected, the higher survival rate, the stronger the material. The effective tensile modulus(ETM) of SFRC is predicted using 2-D multi fiber composites with aligned array and staggered array. It is also found that staggered array shows the better load transfer than aligned array by having a higher ETM at given conditions. By comparing among various theories and FEM results, not only the interactions but also stress transfer between fiber and matrix has a significant influence on the composite modulus and strength. As expected, the ETM increases when both aspect ratio and fiber volume fraction are increased. The ETM of staggered array shows the same results of Halpin-Tsai prediction and believed to have a configuration similar to a practical composite. Also, it is shown that the type of fiber distribution has significant influence on the mechanical properties of composite.

ACKNOWLEDGEMENT

This research was supported by the program for the training of graduate students in regional innovation which was conducted by the ministry of commerce industry and energy of Korean government.

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