High-Strength Ceramics from Waste Glass Fiber and Clay

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Abstract- E-glass fiber is the most common reinforcement used in plastics produced by injection molding.The mass production of E-glass fiber has yielded large quantities of glass fiber which must be disposed of. Much of the waste glass fiber has been buried underground as industrial waste. Fine glass fiber dust from such landfill may cause serious health damage and ecological destruction and landfill sites may also become unavailable in future owing to space constraints. The development of an effective technique for the disposal of waste glass fiber without polluting the environment is therefore strongly desirable. To recycle waste glass fiber effectively and in an environmentally friendly manner, we produced glass fiber reinforced ceramics by mixing clay and waste glass fiber before firing the mixture.We have been able to ascertain suitable manufacturing conditions to produceceramics with high strength.

Keywords – Ceramics, Composite Material, Recycling, Waste Glass Fiber, Clay, Sintering, Bending Strength

I. Introduction

E-glass fiber is produced on a large scale for use as a reinforcementin plastics from injection molding. This mass-production has yielded large quantities of glass fiber which must be disposed of. Much of the waste glass fiber produced so far has been buried underground as industrial waste. Fine glass fiber dust from such landfills may cause ecological destruction and serious damage to health. Furthermore,the shortage of waste disposal areasmay become a serious problem in future. This situation has led to the development of composite materials using natural fibers as an alternative reinforcement to glass fiber[1]-[4]. Although natural fibers are ecological materials,improvements inthereliability oftheir strength and toughness is required.In addition, it is difficult to enhance theincombustibility by adding plastic to the natural fibers.Glass fibers have already been used in large quantities and the development of effective techniquesis required for theirdisposal without polluting the environment [5].Glass fiber reinforced concretefor sub-base materials used in pavementshas been developed[6,7]. Although this technology is effective, it isn't enough for recycling large quantities of waste glass fiber.

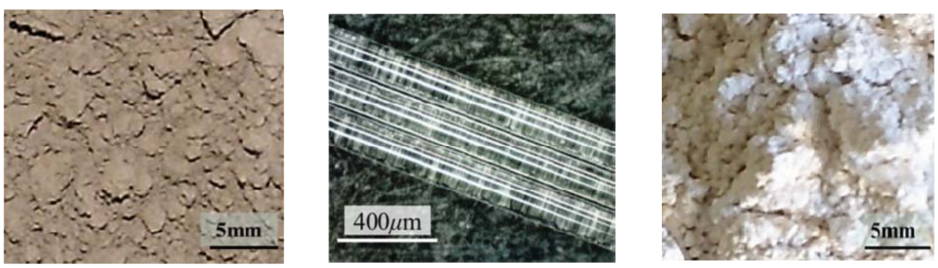
In this study, for the effectiveand environmentally friendly recycling of waste glass fiber, we produced glass fiber reinforced ceramics by mixing clay and waste glass fiber before firing the mixture. Weaimed to develop a simple recycling method that can be used to treat large volumes ofwaste. Several specimens were produced by changing the glass fiber length and clay and glass fibercontent whereafter the bending strength was examined. From the test work and results we established suitable manufacturing conditions to produce ceramics reinforced with glass fiber.

II.MATERIALS AND PRODUCTION METHOD

A. Raw materials –

Figure 1 shows the raw materials used for producing the specimens. Figure 1(a) shows clay produced in Miyazaki Prefecture, Japan, for use in brick or tile manufacture. Figure 1(b) and (c) shows waste E-glass fiber and the glaze used as a sintering additive, respectively. E-glass fiber was provided by San-Techno Corporation with a diameter of approximately 200µm. The mean bending strength of 10 samples was 1.87 GPa. The glaze was used to increase the bonding strength between the glass fiber and clay matrix. The firing temperature when using the glazewas 900°C or less.

Table 1 shows the inorganic chemical compositions of the clay, E-glass fiber and the glaze. The inorganic component analysis was carried out using X-ray fluorescence analysis(Simadz Corp., XRF-1700). E-glass fiber and the glaze contained SiO_2, CaO and Al_2O_3 as main components, while the clay contained SiO_2 and Al_2O_3 as its main components. The CaO component ratios of the E-glass fiber and the glaze were slightly larger than that of the clay.



(a) Clay (b) E glass fiber (c) Sintering additive

Figure 1. (a) Clay, (b) E-glass fiber and (c) sintering additive (glaze) used as raw materials

Table 1 Chemical Compositions of Clay, E-glass Fiber and Sintering Additive

	Clay	**E-glass Fiber**	**Sintering Additive(Glaze)**
Component	**Mass (%)**	**Mass (%)**	**Mass (%)**
SiO_2	**66.0**	**54.9**	**67.0**
Al_2O_3	**22.2**	**16.3**	**8.3**
Fe_2O_3	**4.72**	**0.77**	**0.4**
K_2O	**3.60**	**0.15**	**1.5**
MgO	**1.51**	**-**	**1.7**
CaO	**0.97**	**26.7**	**20.0**
TiO_2	**0.90**	**0.56**	**-**
ZnO_2	**0.01**	**-**	**0.7**

B. Ceramic production –

Table 2 shows the types of specimens and raw material mixing ratio for each specimen. To determine the influence of glass fiber length on composite material bending strength, glass fibersof 0.5 mm or less in length (aspect ratio 3 or less) and 10mm or more (aspect ratio 50 or higher) were mixed with the clay. Specimens A1, A2 and A3 were made to examine the influence of short glass fibers(0.5 mm or less in length) on bending strength. The mixing ratio of glass fiber to total mass varied from 0 to 60%. Zero to 2% glaze was added as sintering additive. The crushed glass fiber was mixed with clay as uniformly as possible.

Specimens B1, B2 and B3 were made to examine the influence of long glass fibers (approximately 10 mm in length) on bending strength. The mixing ratio of the long glass fibers to total mass varied from 0 to 10%. From 0 to 2% glaze was added to the clay. The long glass fibers were mixed randomly with clay. For specimens A1–A3 and B1–B3, the firing temperature was 900°C for use with the glaze.

Specimens C1 and C2 were made to examine the influence of anisotropyon bending strength as a result of glass fiber orientation using long and continuous glass fibers. Specimens were made by mixing clay with glass fibers approximately 10 or 50 mm long. Glass fibers were arranged in a longitudinal direction in the specimen between the clay layers, as shown in Figure. 2. No glaze was added to the mixtureswhich were fired at 1000°C. The specimens were produced using the following procedure.

(1) E-glass fiber was crushed or cut to the sizes shown in Table 2.The clay was crushed to a particle size of 0.5 mm or less.

(2) Clay, E-glass fiber and glaze were mixed according to the mixing ratios in Table 2. Each mass of total mixture was 15.0 g.

(3) The mixtures were solidified in a mold at 9.8 MPa. The molded specimens were 70 mm long, 20 mm wide and approximately 5–10 mm thick.

(4) The molded specimens were heated in an oxidizing atmosphere at a rate of 100 °C h^{-1} tothe firing temperature using an electric furnace(Kyoei Electric Kilns Co., Ltd., Japan, KY-4N), held at the firing temperature for 1 h and then cooled to room temperature in the furnace.

Table 2 Manufacturing Conditions of Composite Materials Made from Clay and E−glass

Specimens	Glass Fiber Length (mm)	Glass Fiber Mixing Ratio (%)	Glaze (%)	Method of Mixing of Glass Fiber
A1	0.5or less	10–60	None	Uniform
A2			1	
A3			2	
B1	10	2–10	None	Random
B2			1	
B3			2	
C1	10	2–15	None	Unidirectional
C2	50			

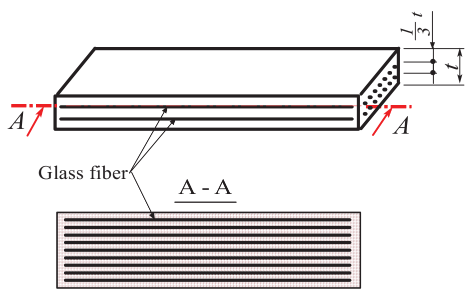


Figure2.Unidirectionally reinforced specimens C1 and C2

C. Strength test –

Four-point bending tests were carried out to determine specimen strength. Tests were performed using a universal testing machine (Shimadzu Corp., AG-X50kN) at a crosshead speed of 0.5 mm/min. The maximum bending stresswas calculated using Equation (1) from the measured maximum load.

$$\sigma_f = \frac{3P(L-a)}{2bh^2} \quad (1)$$

where P is the maximum load, L is the distance between the lower supporting points, a is the distance between the upper loading pointsand b and h are the specimen rectangular cross sectional width and depth, respectively. In this study, L =26 mm and a =10 mm.

III. Experimental Results and Discussion

A. Strength test –

Mixing of glass fiber with aspect ratio of 3 or less

Figure 3 shows examples of specimens made from clay and E-glass fiber (Fig. 3(a)) and the surfaces of specimens observed using an optical microscope (Fig. 3(b)).

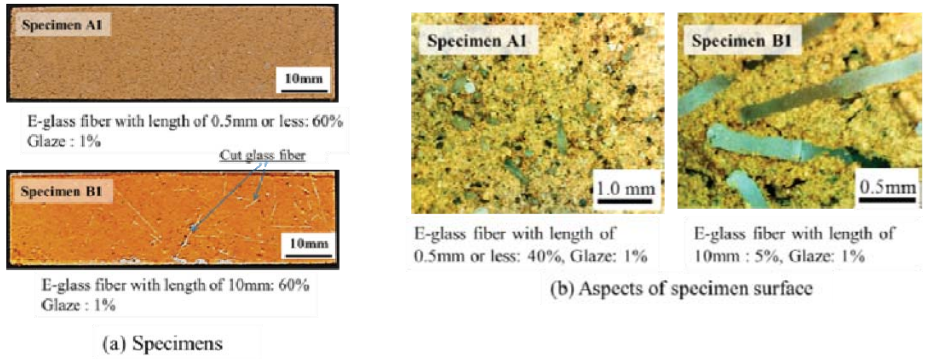


Figure 3.(a) Photographs of specimens and (b) aspects of the surface structures

Figure 4(a) shows the bending strength of specimens A1, A2 and A3 made by the uniform mixing of glass fiber 0.5 mm long or less (aspect ratio 3 or less) with clay. The plotted points are average values of the bending strength of five specimens and the error bars show the standard deviation. The x-axis expresses the mixing ratio (mass %) of the glass fiber. The bending strength of specimens A1, A2 and A3 increased as the glass fiber mixing ratio increased. The bending strength of specimen A1 without glaze increased up to approximately1.8 times the ceramic strength without glass fiber, when a ratio of 60% glass fiber to total mass was mixed with clay. The strength increment was small when the mixing ratio of glass fiber was small (20% or less). The bending strength of specimens A2 and A3 with glaze increased significantly as the mixing ratio of glass fiber increased, andbecame fairly high in comparison with that of specimen A1.

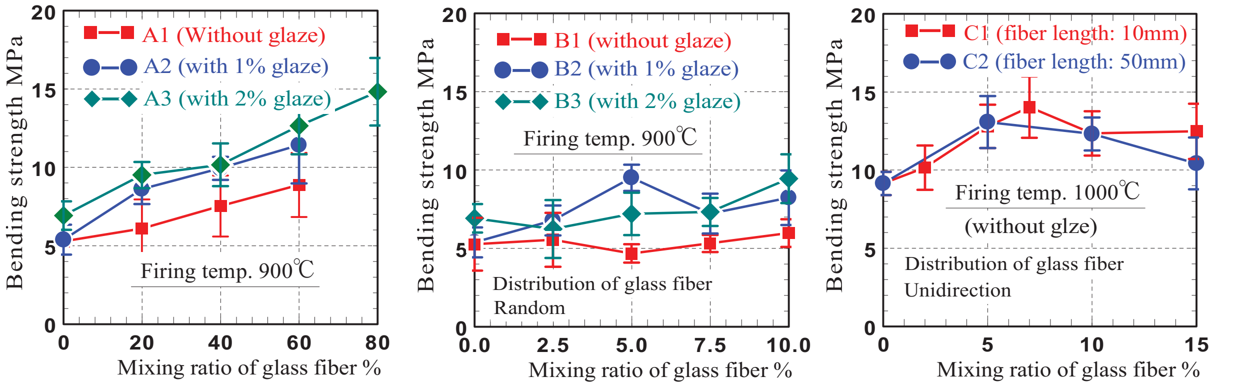
A high strength specimen could be producedby mixing both the glass fiber and glaze with clay. The bending strength of specimen A3 was slightly higher than that of specimen A2. In terms of composite material manufacturing cost, the quantity of glaze used should be minimized. Therefore, approximately 1% glaze is effective for improvingbending strength.

A bending strength of 5 MPa or more is required for sub-base materials such as interlocking blocks used in pavements [8]. The ceramic without glass fiber fired at 900°C does not satisfy this strength requirement. Ceramics made by mixing glass fiber with clay comply with the standard when the mixing ratio of glass fiber is approximately 40% or higher. Ceramics made by mixing both glass fiber and glaze with clay meet the standard when the glass fiber mixing ratio is 20% or higher. The bonding strength between the glass fiber and the clay matrix is increased.Such an improvement in strength can be greatly advantageous in practical applications.

Mixing of glass fiber with aspect ratio of 50 or higher

Figure 4(b) shows the bending strength of specimens B1, B2 and B3 made by the random mixing of glass fibers 10 mm or more in length (aspect ratio 50 or higher) with clay. The bending strength of the specimens increased only slightly with the mixing of glass fibers but increased with glaze addition. The overlap and random distribution of the glass fiber seems to cause this response [9].

Figure 4(c) shows the bending strength of specimens C1 and C2 in which glass fibers 10 or 50 mm in length were mixed in the longitudinal direction between the clay layers. The bending strength increased up to an approximate 5% glass fiber mixing ratio and then decreased. The bending strength is thought to decrease because the arrangement of glass fibers is disrupted at a glass fiber mixing ratio greater than 5%. This suggests that the long and continuous glass fibers should bedistributed in the clay matrix so that they do not come into contact with each other in the manufacturing process.Ceramics with an appropriate arrangement of glass fibers will have the higher strength.

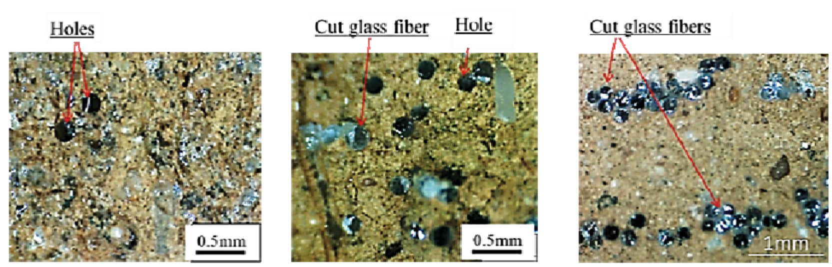


(a) Fiber length: 0.5mm or less (b) Fiber length: 10mm (c) Fiber length: 10mm or 50mm

Figure 4.Bending strength of specimens

B. Strengthening mechanism of ceramics by glass fiber –

Figure 5 shows fractured surfaces after completion of the bending tests for specimens A2, B1 and C2. A few holes made by the glass fiber being pulled out from the matrix are observedfor the fractured surface of specimen A2. For the fractured surface of specimen B1, holes are made by glass fibersbeing pulling out ofthe matrix and glass fibers have been severed by crack growth. For the fractured surface of specimen C2, all glass fibers have been severed by crack growth. For specimens made from clay and glass fibersof 0.5 mm length or less, the crack extension resistance increases by the pulling out of the glass fiber from the matrix, thereby increasing the bending strength. For specimens in which long and continuous glass fibers were mixed by being arranged systematically in the clay matrix, the crack extension resistance caused by the cutting of glass fibers increases and the bending strength therefore increases.



60% E glass fiber, 2% glaze
Fiber length: 0.5mm or less
(a) Specimen A2

5% E glass fiber, 1% glaze
Fiber length: 10mm
(b) Specimen B1

5% E glass fiber,
Fiber length: 50mm
(c) Specimen C2

Figure 5. Fractured surfaces of specimens

IV.CONCLUSIONS

To recycle waste glass fiber effectively, we produced glass fiber reinforced ceramics by mixing clay and waste E-glass fiber before firing the mixture. We obtained the following results:

(1) The bending strength of specimens made by the uniform mixing ofshort glass fibers 0.5 mm or less in length (aspect ratio 3 or less) with clay increased with increasing mixing ratio of glass fiber but the increase in strength was small.

(2) The mixing of short glass fiber 0.5 mm or less in length and a small quantity of glaze with clay yielded a ceramic with higher strength asthe bonding strength between the glass fiber and clay matrix increases.Inclusion of a certain quantity of glaze in the mixture is very effective for improving the strength.

(3) When long and continuous glass fibers(aspect ratio 50 or higher) were mixed randomly with clay, the ceramic bending strength increased slightly.When the long and continuous glass fibers were distributed regularly in the

clay matrix,the ceramic bending strength increased up to an approximate 5% glass fiber mixing ratio and then decreased. From these results, to increase the strength,the glass fibers must be distributed regularly in the clay matrix so as not to come into contact with oneanotherduringthe manufacturing process.Ceramics with an appropriate arrangement of glass fibers will have the higher strength.

V. ACKNOWLEDGEMENTS

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