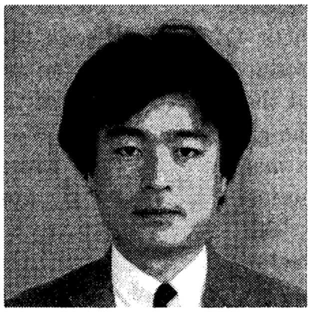
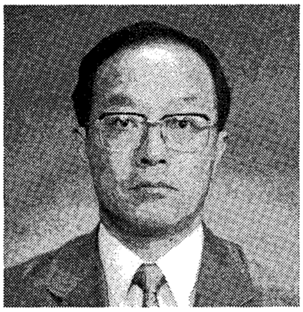
CONCRETE LIBRARY OF JSCE NO. 21, JUNE 1993

DURABILITY AND MICROSTRUCTURE OF GLASS FIBER REINFORCED CONCRETES PRODUCED BY PREMIXING

(Reprint from proceedings of JSCE, No.451/V-17, 1992.8)

Shin-ichi IGARASHI and Mitsunori KAWAMURA

SYNOPSIS

Glass fiber reinforced concretes (GFR concrete) were produced by premixing method. Changes in some mechanical properties of GFR concrete with time were investigated up to the age of 5 years. Reductions in strength and toughness were observed at relatively early ages, compared to GRC produced by spray method. Differences in time-dependent changes in the mechanical properties between specimens stored under several different conditions were not great. This result may be due to the dispersion of strands into individual filaments and/or loosening of strands during mixing.. Loosening of strands enables hydration products to easily deposit at the interfacial zone and within spaces among filaments. Therefore, effects of aging mechanisms on the degradation in mechanical properties in GFR concretes produced by premixing appear at earlier ages than in the ones produced by spray method.

Keywords : GRC, durability, microstructure, interfacial zone

Shin-ichi Igarashi, a member of JSCE, is a research associate, Department of Civil Engineering , Kanazawa University, Japan. He has been involved in research on microstructure and mechanical properties of FRC composite.

Mitsunori Kawamura, a member of JSCE, is a professor, Department of Civil Engineering, Kanazawa University, Japan. He has been active in research on alkali-aggregate reaction, effects of flyash on properties of concrete, microstructure and fracture of concrete and FRC composite.

---

1. INTRODUCTION

Glass fiber reinforced cement (GRC) is mostly used as a panel of building materials. High strength and resistibility against impact load of GRC are obtained by the incorporation and uniform dispersion of a sufficiently large amount of glass fibers. Furthermore, the resistance against cracking during the transportation and handling of GRC products are also enhanced. There are various methods to produce GRC products. Of those methods, the spray - up method developed based on the technology used in the production of FRP is the most reliable method because of the excellence in the quality itself and the quality control of the final products of GRC. Usually, the term of "GRC" is used for the glass fiber reinforced cement produced by the spray method. However, if GRC is used as a member of relatively large scale of concrete structure in the construction site, glass fiber reinforced "concrete" (named GFR concretes, hereafter) with thick section may be preferable. Taking account of the construction process and long term serviceability of the concrete structure, premixing concretes containing glass fibers is the most common and effective method to produce such massive concrete structures.

The method of premixing itself has some disadvantages, compared to the spray method. Uniform dispersion of fibers in concrete is only possible at a relatively small volume fraction of fibers, and a higher water cement ratio of concrete is required. Furthermore, fibers are damaged by mixing, and loosening of the strand and 3D random dispersion of fibers occur during the mixing process [1]. Therefore, the loss of efficiency of glass fiber reinforcement may be inevitable to some extent. However, recently, the modified procedure of premixing and special glass fibers for the production of GFR concretes by the premixing method have been developed to obtain the better performance of GFR concretes.

GRC itself has a serious problem on durability in that its strength and toughness decrease with time under a wet environment. This durability problem of GRC has been explained in the following two ways. One is based on the deterioration of glass fibers due to chemical attack by the high alkaline pore solution in cement matrix [2]. Another is based on the microstructural changes resulting from the growth of hydration products, mainly $Ca(OH)_2$, between the glass filaments [3,4]. Several means have been proposed to improve the durability of GRC [5,6,7,8].

Characteristics of the fresh mixture of GFR concretes and their relation to the mechanical properties of the hardened composites have been investigated hitherto [1,9,10,11]. However, there are few studies on the long term performance of GFR concretes produced by premixing. Particularly, taking into account the significant effects of microstructural changes in the vicinity of glass fiber strands on the mechanical properties of GRC composites produced by the spray method, the time dependent changes in mechanical properties of GFR concretes and the microstructure of them are important problems to be solved since the state of glass fibers within the composite is different from that in GRC produced by the spray method.

In this study, effects of various environmental conditions on the long term performance of GFR concretes placed for long times are investigated. Effects of loosening of glass fiber strands during premixing on the durability of GFR concretes were also discussed. Comparison in durability between GFR concrete and common GRC is also made with the emphasis on their microstructural features.

2.EXPERIMENTAL

2.1 Materials

The cement used is ordinary Portland cement. River sand and crushed gravel of which the maximum grain size is 15mm are used as fine and coarse aggregates. Physical properties of those aggregates are given in Table 1. Two types of alkali resistant glass fiber strands for premixing (the glass fiber A and the glass fiber B, hereafter) are used. Physical properties of glass fiber A and B are given in Table 2. As seen in Table 2, there is no difference in mechanical properties of filaments themselves between both types of fibers, but individual filaments in glass fiber B are more strongly bonded into strands by a certain size than in glass fiber A.

2.2 Mix Proportion of Glass Fiber Reinforced Concretes

The mix proportions of GFR concretes are given in Table 3. In this study, concretes with high water:cement ratio and high unit cement content are adopted to acquire the slump values of 10 and 5cm for the volume fraction of fibers of 1% and 1.5%, respectively. Water:cement ratio of GFR concretes was decided considering the durability of concrete based on JSCE specification for concrete [12].

Table 1 Physical properties of fine and coarse aggregate

	Spec. Gravity	Absorption(%)	F.M.	G_{max}(mm)
Sand	2.64	1.26	2.46	
Gravel	2.62	2.20	6.21	15

Table 2 Properties of glass fiber strands

	Glass Fiber A	Glass Fiber B
Diameter(μm)	13	20
Number of Filaments	100	160
Specific Gravity	2.78	2.78
Tensile Strength(kgf/cm^2)	25000	25000
Young's Modulus(kgf/cm^2)	7.5×10^5	7.5×10^5
Length(mm)	24	25

Table 3 Mix proportion of GFR concretes

Slump (cm)	Air (%)	W/C	s/a (%)	Unit Content(kg/m^3)				V_f (%)	Type of Fiber Used
				Water	Cement	Sand	Gravel		
10	5±1	0.65	65	207	309	1103	594	0	-
10	5±1	0.65	65	333	512	753	406	1.0	Glass Fiber A
5	5±1	0.65	65	186	286	1154	618	0	-
5	5±1	0.65	65	358	550	692	369	1.5	Glass Fiber A or B

2.3 Production and Storage Conditions of Specimens

Mixing of concretes was made by the Omni type mixer to minimize damages and loosening of glass fiber strands caused by mixing. Glass fiber strands were little by little added into fresh concretes at a low speed of rotation. After adding glass fiber strands completely, the concrete was further mixed for 1 minute to insure the uniform dispersion of glass fibers. Cylindrical specimens ($\phi 100mm \times 200mm$) and $100 \times 100 \times 400mm$ prisms were produced. Those cylindrical and prismatic specimens had been cured in water at 20 °C for 28 days, and then they were placed in five different environments. : (a) in water at 20 °C, (b) in a wet atmosphere at 20°C, 90% R.H., (c) in drying-wetting (i.e. the condition (a)-(e)) biweekly repetitions, (d) in weathering at Kanazawa, (e) in a dry atmosphere at 20°C and 60% R.H..

2.4 Tests Procedures

The following tests were carried out at prescribed ages. Three specimens were used for each test.

(1) Flexural Strength Test
Prismatic specimens of GFR concrete were loaded in the third-point bending using an Instron type testing machine. Deflection at the center of span of 300mm was measured with LVDT to obtain the load-deflection curve of GFR concretes. According to a JSCE specification for the design and manufacture of steel fiber reinforced concretes [13], the flexural toughness of GFR concrete was evaluated by the area under the load-deflection curve up to 2mm of deflection.

(2) Splitting Tensile Strength Test
Splitting tensile strength of GFR concrete was obtained by the use of the universal testing machine, according to JIS A 1113.

(3) Charpy Test
The modified Charpy tester for concrete specimen was used to evaluate the energy absorption of the specimen during impact loading [14].

(4) SEM Examination
A sample was taken from the fracture surface of GFR concrete specimens after flexural strength test. The sample which had been dried in the vacuum drying oven at a room temperature for 24 hours, was coated with gold for SEM examination.

3. RESULTS AND DISCUSSION

3.1 Effect of the Storage Conditions on the Mechanical Properties of GFR Concretes

Fig.1 shows the time dependent changes in flexural strength of GFR concretes. Flexural strength of the concretes decreased with time in all storage conditions. GFR concretes continuously stored in water seems to have the smallest strength of all specimens, although differences in flexural strength between the specimens stored under various environments were relatively small. Comparing the strength of GFR concretes with that of usual concretes, as given in Fig.1, it is found that the increase in flexural strength by glass fiber reinforcement was reduced with time. As a result, there were only little differences in flexural strength between the concretes with and without glass fibers at the age of 6 months.

Typical load - deflection curves obtained for the specimens stored in water and a wet atmosphere are given in Fig.2(a) and (b), respectively. The shape of the curves was very similar to each other. There was also little difference in the deflection at the maximum load between both, and the deflection itself slightly reduced with time. Flexural property of fiber reinforced concretes is generally characterized by the specific values of modulus of rupture (M.O.R.) and the limit of proportionarity (L.O.P.). The value of M.O.R. and L.O.P. correspond to the maximum load attained and the end of linear part of the curve, respectively. The difference between the load at L.O.P. and M.O.R. is the load bearing capacity of glass fibers which bridge matrix crack faces without rupture. The value of L.O.P. is generally controlled by the mechanical property of matrix.

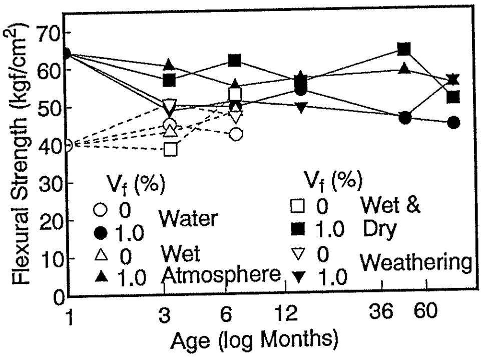


Fig.1 Changes in flexural strength of GFR concretes stored in various conditions.

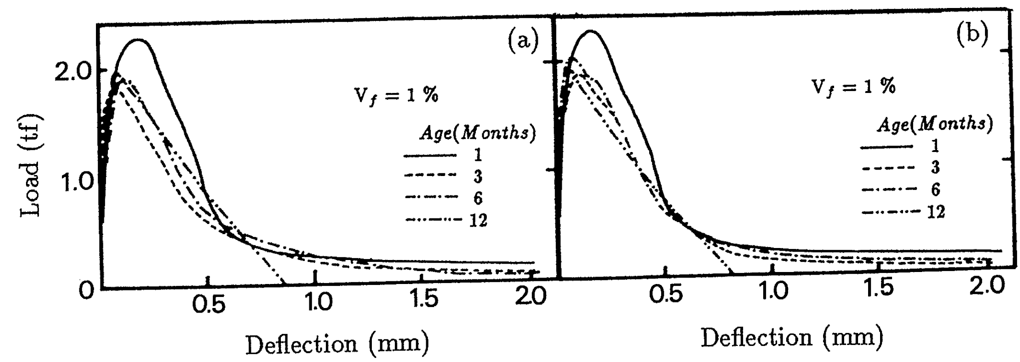


Fig.2 Load-deflection curves of GFR concretes stored in (a) water (b) wet atmosphere.

The values of L.O.P. and M.O.R. for the specimens stored in water and a wet atmosphere are given in Table 4 . There are differences between L.O.P. and M.O.R. at early ages up to 1 month. However, substantial differences between both values are not present at longer ages. Namely, the flexural strength of GFR concretes is mainly controlled by the strength of their matrices at later ages. A single matrix crack was observed during loading. Neither multiple cracks nor discrete cracks were observed during testing. Therefore, the toughness in GFR concrete was mostly given by the pull-out work of glass fibers which constrain the extension of matrix cracks by bridging cracks. However, taking account of the reduction of differences between L.O.P. and M.O.R., and steepening of the descending part of load-deflection curves with time, it is concluded that fibers bridging crack faces were broken in turn as matrix cracks extended.

Table 4 Comparison of values of L.O.P. and M.O.R. (V_f=1%)

Storage	Age (months)	1	3	6	12
Water	L.O.P(kgf/cm^2)	50.7	39.0	49.0	51.0
	M.O.R(kgf/cm^2)	64.5	50.3	49.6	53.9
	M.O.R.−L.O.P	13.8	11.3	0.6	2.9
Wet Atmosphere	L.O.P(kgf/cm^2)	50.7	57.0	54.8	55.8
	M.O.R(kgf/cm^2)	64.5	60.6	55.0	56.9
	M.O.R.−L.O.P	13.8	3.6	0.2	1.1

Fig.3 shows the changes in toughness of GFR concretes with time. Toughness drastically decreased between the age of 1 and 3 months, followed by the gradual decrease up to the age of 12 months. After 12 months, however, the contribution of glass fiber reinforcement to the toughness of concretes was completely lost so that the failure mode of GFR concretes was brittle regardless of the storage conditions.

Age-embrittlement of GFR concretes also appeared in the results of the impact strength test. The energy absorption during the impact loading is given in Table 5. The energy absorbed in the impact strength test decreased with time.

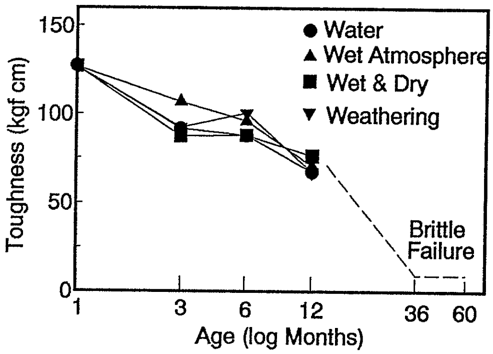


Fig.3 Effect of aging in various conditions on the toughness of GFR concretes.

Table 5 Effect of aging in various conditions on the energy absorbed in the specimens during impact loading (kgf·m).

V_f:0%	Age (Months)					
	1	3	6	12	36	60
Water	9.5	8.9	7.8			
Wet Atmosphere		9.5	7.6			
Dry and Wet		8.7	7.8			
Weathering		10.0	8.3			
V_f:1%						
Water	11.6	10.0	9.6	9.0	9.1	8.6
Wet Atmosphere		10.0	10.3	9.1	9.0	8.4
Dry and Wet		10.0	9.9	8.8	9.0	8.1
Weathering		10.4	10.1	8.7	8.8	8.4

Majumdar et al. [15,16] have investigated the time-dependent changes in mechanical properties of GRC produced by the spray suction method. They showed that the mechanical properties of GRC was greatly dependent on the storage conditions, and that GRC stored in a dry atmosphere (18 ~ 20 °C, 40% R.H.) maintained the initial strength of 28-day old specimen up to the age of 10 years. However, the flexural strength of GRC stored in water decreased gradually for the first year, and thereafter, the strength continued to decrease but to a lesser extent up to 5 years. Even at the age of about 10 years, the flexural strength of GRC stored in water slightly decreased. They reported that the flexural strength of the specimens subjected to weathering decreased with time continuously for 10 years. Furthermore, they reported that considerable reduction in the strain at L.O.P. and the ultimate strain with time occurred in specimens stored in water and natural weathering. They concluded from these results that the pseudo-ductility in GRC due to the pull-out energy of fibers disappeared during the storage of specimens in a wet condition.

Comparing the mechanical properties of GRC produced by the spray method with those of GFR concretes in this study, the time-dependent reduction in flexural strength, toughness and resistibility against impact load are found in both. However, the influence of curing conditions on the time-dependent behavior of mechanical properties of GFR concretes was not so well-found as in GRC. Particularly, brittle failure of specimens was observed in any storage conditions at the age of 1 year whereas such a short term embrittlement was not reported for GRC produced by the spray method [15,16]. This early degradation of GFR concretes may be attributed to small fiber contents in these concretes produced by premixing, less efficiency of reinforcement of randomly oriented fibers in concretes and a wet condition of curing in the concretes.

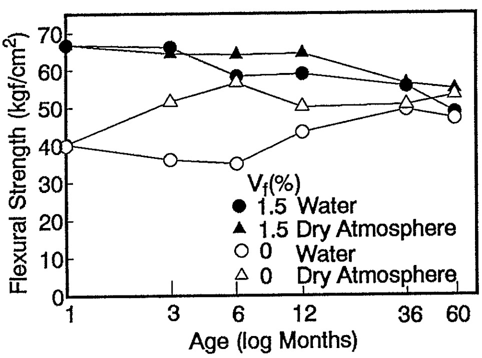


Fig.4 Flexural strength of GFR concretes at various ages in water and dry atmosphere storage.

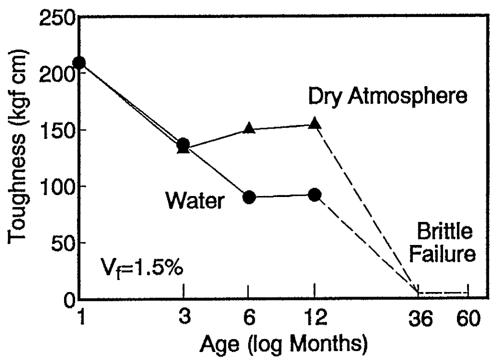


Fig.5 Toughness of GFR concretes at various ages in water and dry atmosphere storage.

Fig.4 shows the effect of storage condition on the reduction of flexural strength of GFR concrete with time at the fiber content of 1.5%. The reduction in flexural strength of GFR concretes with time was delayed compared to that in GFR concretes at the fiber content of 1.0% (Fig.2). The initial flexural strength was kept in a dry atmosphere for at least 1 year. However, the flexural strength of GFR concretes stored even in a dry atmosphere decreased after 1 year as specimens stored in water did. The increase in flexural strength given by the glass fiber reinforcement was completely lost even in a dry atmosphere at the age about 5 years (Fig.4).

Fig. 5 shows the toughness of GFR concretes with the volume fraction of 1.5%. Toughness of GFR concrete specimens decreased during the period from 1 to 3 months under both the two storage conditions. This descending tendency with time in toughness are similar to that of the specimens with the fiber content of 1.0%. However, in the specimen stored in a dry atmosphere, a relatively high toughness at 3 months was maintained up to 1 year, while the toughness of the specimen stored in water further decreased with time. Thus, the improvement in toughness due to the fiber reinforcement in specimens in a dry atmosphere was effective only during the period from 3 months to 1 year. This result shows that the dependence of age-embrittlement of GFR concretes on curing conditions was not so conspicuous as in GRC produced by the spray method. Furthermore, it should be noticed that all specimens aged longer than 1 year fractured in such brittle manner as in the unreinforced concrete matrix, and that the toughness improvement by glass fiber reinforcement was completely lost at that age. The age-embrittlement of GFR concretes was also reflected in the impact strength (Table 6). However, the rate of reduction in the energy absorption in the impact test was relatively small in the specimens stored in a dry atmosphere. As a result, the improvement in the resistibility against the impact load in the specimen stored in a dry atmosphere remained to some extent. The difference in the splitting tensile strength between GFR concretes and usual concretes was considerably small after 3 months old (Fig.6).

Table 6 Energy absorbed in GFR concrete specimens stored in water and dry atmosphere (kgf·m)

V_f:0%	Age (Months)					
	1	3	6	12	36	60
Water	8.3	8.3	8.3	9.3	10.0	9.1
Dry Atmosphere		8.3	8.5	7.6	9.9	8.8
V_f:1.5%						
Water	10.4	9.2	9.8	8.5	10.0	9.4
Dry Atmosphere		9.8	11.0	9.6	11.2	10.1

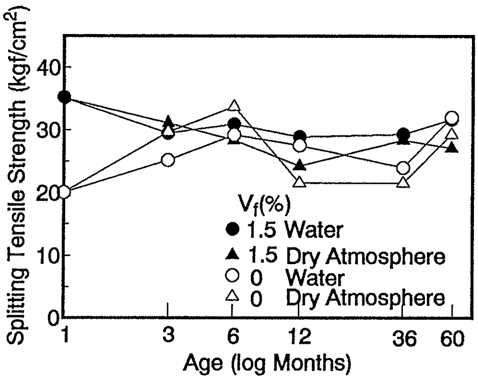


Fig.6 Changes in splitting tensile strength of GFR concretes with time.

It is summarized that the toughness of GFR concretes decreased with time as in GRC produced by the spray method. Particularly, the reduction in toughness occurred at relatively early ages, compared to the common GRC. However, the effect of the storage condition on the degradation of mechanical properties of GFR concretes was not clear. Majumdar et al [15] pointed out that the proportion of glass fibers per unit volume of hardened cement was an important factor in the durability of GRC, and that it took a relatively long time for the effect of a considerable densification of the interface due to cement hydration on the mechanical properties to exhibit in GRCs containing large amounts of glass fibers. The addition of relatively small amounts of glass fibers in GFR concretes produced by premixing could lead to early degradation of their mechanical properties. However, a small increase in fiber content from 1.0 to 1.5% failed to decrease the rate of reduction in toughness of GFR concretes.

3.2 Effect of Separation of the Strand on the Mechanical Properties of GFR Concrete

The degree of separation of the glass fiber strand into smaller units can greatly affect the durability of GFR concretes. Nair[17] investigated the microstructural changes around glass fiber strands which remained integral as short bundles of filaments. In such a case, only outer filaments of the strand have possibility to suffer the chemical attack by a high alkaline pore solution. Therefore, the deterioration of glass fibers by the chemical attack may not be so significant as a whole. As a result, glass fiber strands, which act as a single reinforcing element, can be pulled out because of less frictional bond strength between strands and the matrix at early ages. However, at the later ages, the hydration products can deposit in spaces among filaments of strands. All filaments in a strand can suffer the deterioration due to the chemical attack as well.

On the other hand, from the viewpoint of the microstructural changes due to the deposition of hydration products in the interfacial zone between glass fibers and cementitious matrix and in the spaces within a strand, loosening of strands enables hydration products to deposit around each filament. Photo 1 shows the fracture section of GFR concrete with the glass fiber A. Separation of the strand into each filament was found to occur. Individual filament directly contacted with the cement paste matrix. Such separation of strands into smaller units promoted embrittlement of GFR concrete due to both of the chemical attack and the microstructural changes.

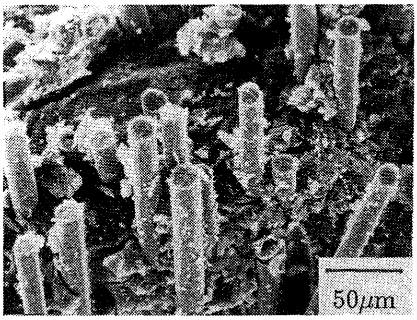


Photo 1 Fracture surface of GFR concrete.

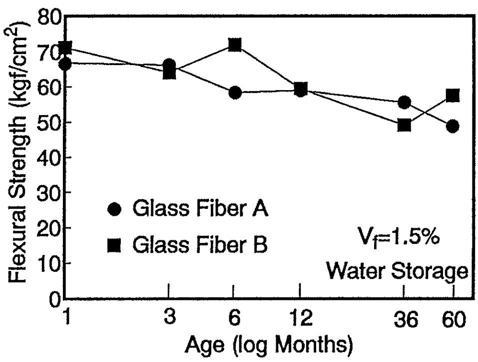


Fig.7 Comparison of flexural strength between GFR concretes with glass fiber A and B.

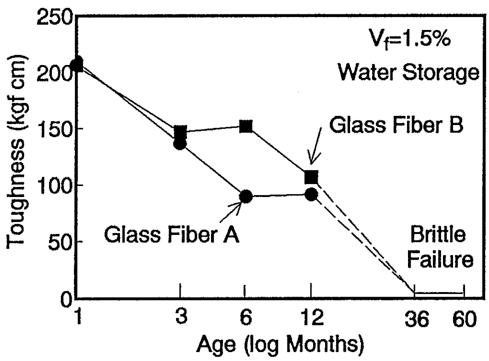


Fig.8 Comparison of toughness between GFR concretes with glass fiber A and B.

The degree of loosening of strands can be varied to some extent by the type of size and the surface treatment of fibers. The size used for glass fiber strand functions to protect surfaces of glass fibers from damages during mixing, and to improve the bond strength of fiber to cement matrix [18,19]. Therefore, the size in the strand affects not only the degree of separation of strands but also the interfacial microstructures around glass fibers [20,21].

Comparison between flexural strength of GFR concretes with the glass fiber A and the glass fiber B is shown in Fig.7. The decreasing tendency in flexural strength with time in the specimens with the glass fiber A and B was not so different from each other.

Fig. 8 shows the comparison in toughness between GFR concretes with the glass fiber A and B. Significant differences in toughness were not seen between both GFR concretes except the value at the age of 6 months. Brittle failure occurred in specimens with the glass fiber B at the age longer than 1 year. Namely, the improvement of toughness by the use of the glass fiber B was lost after 1 year.

Little differences in tensile and impact strength between specimens with the glass fiber A and B were found (Fig.9, Table 7).

Consequently, it is concluded that improvement of a strand by the use of a specific size failed to prevent GFR concretes from their early degradation in mechanical properties.

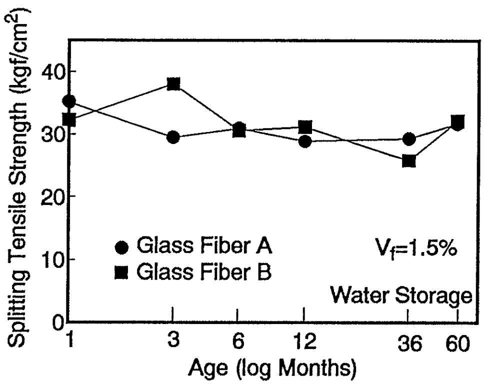


Fig.9 Comparison of splitting tensile strength between GFR concretes with glass fiber A and B.

Table 7 The energy absorbed during impact loading in the specimens with glass fiber A and B (kgf·m)

V_f:1.5%	Age (Months)					
	1	3	6	12	36	60
Water(Fiber A)	10.4	9.2	9.8	8.5	10.0	9.4
Water(Fiber B)	11.5	10.5	9.0	10.2	9.8	9.2

3.3 SEM Examination of Fracture Surfaces of GFR Concretes

Photo 2 (a) and (b) show the fracture surfaces of 28 days old specimens with the fiber content of 1.0% and 1.5%, respectively. Hydration products were deposited on the surfaces of glass fibers, but the severe damage of fiber such as etch pits and the reduction in cross sectional area of fibers caused by chemical attack were not found (Photo 2(a)). As shown in Photo 2(b), a layer of well oriented $Ca(OH)_2$ crystals of about 5μm in width had been already formed at the interface between filaments and concrete matrix.

Photo 3(a) and (b) show SEM micrographs of fracture surfaces of a GFR concrete stored in water for 3 months. Much hydration products are found to be deposited on the surface of a filament (Photo 3(a)). However, all of glass fiber filaments were not covered with hydration products. As shown in Photo 3(b), in some regions, $Ca(OH)_2$ crystals were found in the interfacial zone around a filament, while only a little hydration products were deposited on the surfaces of glass fibers.

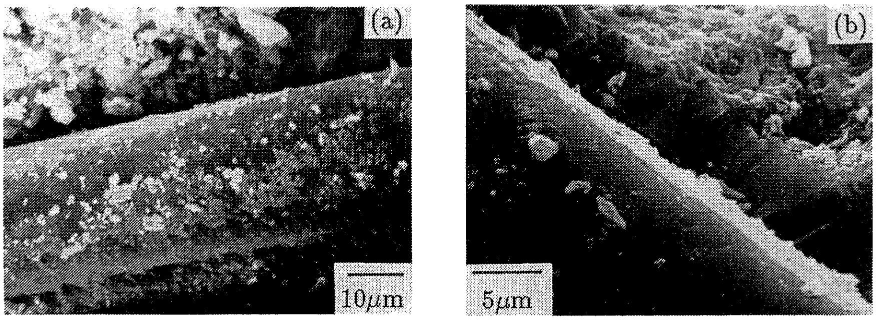


Photo 2 Fracture surfaces of GFR concrete at the age of 28 days; (a) less hydration products on the surface of a filament (b) deposition of $Ca(OH)_2$.

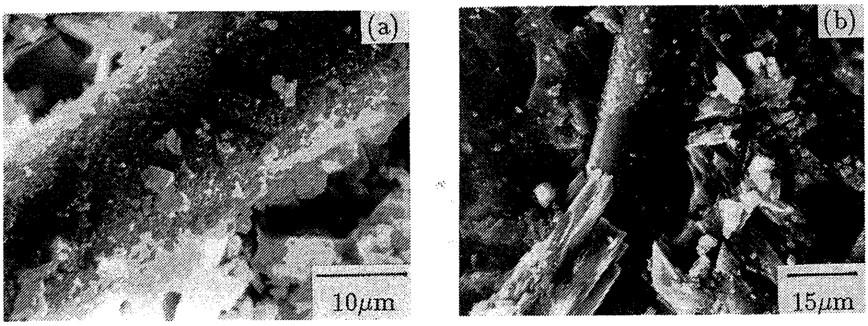


Photo 3 Fracture surface of GFR concrete aged 3 months in water ; (a) much hydration products on the surface of a filament (b) growth of $Ca(OH)_2$ at the interface.

Photo 4 shows the fracture surface of the GFR concrete cured in a dry atmosphere for 3 months. Most of filaments were broken even in GFR concretes stored under a dry environment. Generally, glass fiber strands are pulled out from matrix in several-month old GRC when the GRC produced by the spray method is stored in a dry atmosphere. Less densification of the interfacial zone and the formation of vacant spaces between filaments in GRC products stored in a dry environment make it possible for the glass fibers to be pulled out without breaking. However, in GFR concretes, such extraction of filaments from the cement matrix without breaking was impossible even if the GFR concrete specimens were kept in a dry atmosphere for a relatively short term.

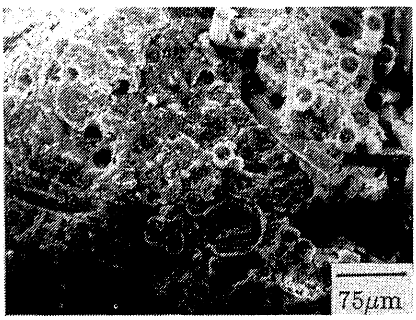


Photo 4 Fracture surface of 3 months old GFR concrete in a dry atmosphere.

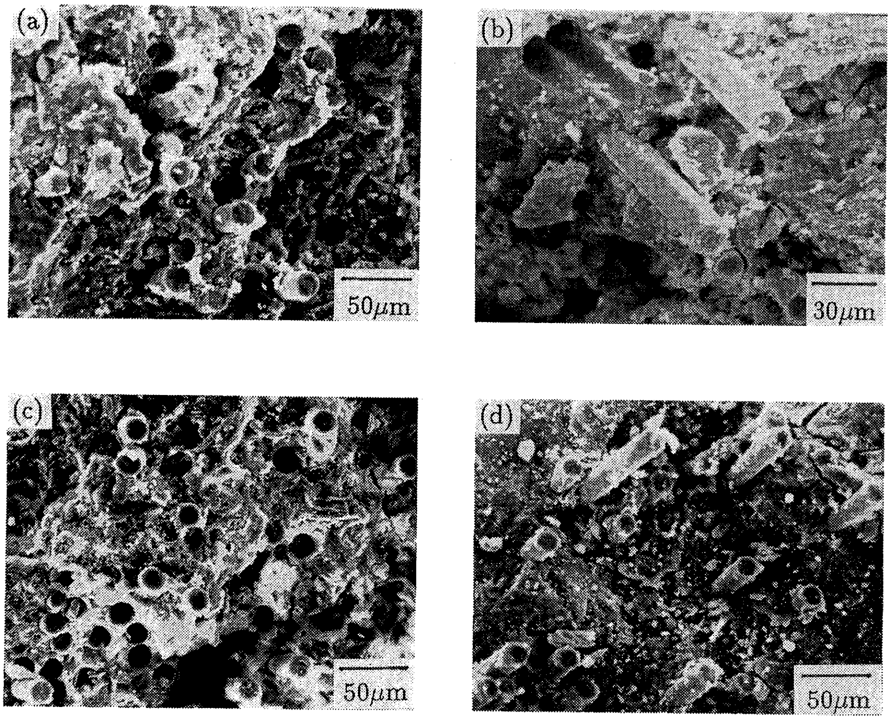


Photo 5 Fracture surfaces of GFR concretes at the age of 1 year; (a) in water (b) in wet atmosphere (c) weathering (d) in the cycle of wetting and drying.

Photo 5(a) ~ (d) show SEM micrographs of the fracture surfaces of GFR concretes with the fiber content of 1.0% which were stored in various environments for 1 year. All of the filaments in GFR concretes stored in any condition were broken. The length of the portion of broken glass filaments extruded out of the matrix was shorter than 100μm at most. On the other hand, mirror zones suggesting tensile failure were found in the cross section of filaments within 1 year old specimens (Fig.10, Photo 6). The mirror zone radius is related to the tensile breaking stress, as given in Eq.(1) [22,23].

$$\sigma_f = Ar^{-1/2} \tag{1}$$

where,

σ_f : tensile strength of a filament
r : mirror zone radius
A : mirror zone constant

Mirror zone constant (A) is expressed by the use of the stress intensity factor (K_{IC}) and half of the critical flaw size (a), as given in Eq.(2).

$$A = K_{IC}(\frac{r}{a})^{\frac{1}{2}} \tag{2}$$

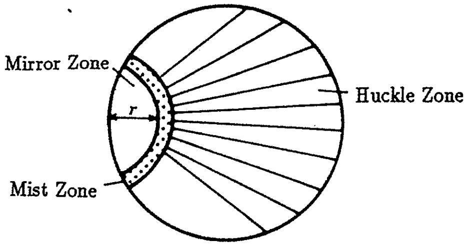


Fig.10 Schematic illustration for mirror zone.

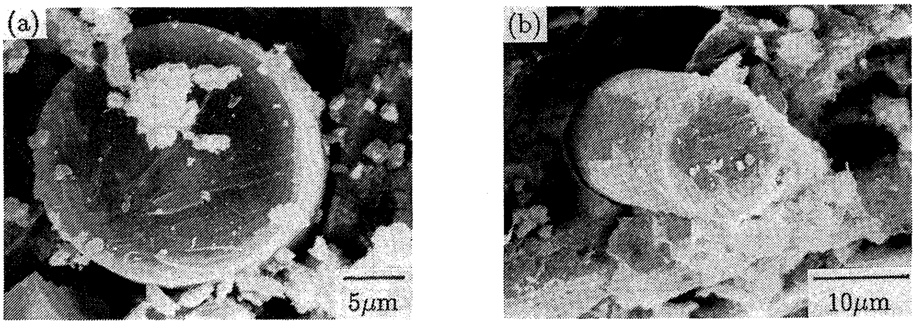


Photo 6 Failure section of glass filaments showing mirror zone ; (a) in water (b) weathering.

In order to estimate the tensile strength of glass fibers in GRC, Jaras[23] have applied Eq.(1) to the cross sections of filaments which appeared on fracture surfaces of GRC. They reported that the mirror zone constant for AR glass fiber (Cem FIL) was 2.37MN$m^{-3/2}$. Using this value for filaments in fractured surfaces in this experiment (Photo 6), the strengths obtained ranged from 12000 to 14000 kgf/cm^2. This value is as large as about 50% of the nominal strength of glass fiber strand used in this study. The ratio of mirror zone radius to flaw size generally ranges from 10 to 13 in silicate glasses [23]. Thus, it may be deduced that the reduction in tensile strength of glass filaments in this experiment was due to the presence of flaw of 0.3 $\sim$ 0.6 μm in size in glass fibers in the composite since the mirror zone radius measured by the use of SEM micrograph ranged from 2 to 3 μm. Etch pits by a chemical attack on the surfaces of glass filaments is considered to be a flaw in these glass fibers. However, the evidence for any chemical attack to the glass fiber have not been reported in GRC specimens cured for relatively short times. Glass filaments removed from 1 - year old specimens of GRC maintained their original tensile strength [24]. Furthermore, the tensile strength of a glass fiber immersed in a high alkaline solution was retained for a long term [25]. Therefore, the reduction in tensile strength estimated from the mirror zone radius of glass filaments in this study may be attributed to flaws in fibers made during mixing of the GFR concretes. However, such flaws have already existed at early ages. Therefore, the degradation of the mechanical properties of GFR concretes with time cannot be explained only by the presence of such flaws in glass fibers.

Bentur[3] has summarized the effectiveness of various mechanisms responsible for the loss in strength and toughness with time , as given in Table 8, considering the deterioration due to both chemical attack and microstructural changes. The results in Table 8 are deduced by relating the results of SEM examinations and the tensile strength tests of glass filaments within the composites to the mechanical properties of GRC produced by the spray method. However, as mentioned previously, loosening and separation of strands in GFR concretes promoted the growth of hydration products around each filament at early ages (Photo 7). Therefore, the degradation in mechanical properties in early ages is due not to physical damages but to the deposition of hydration products.

Table 8 Effect of aging mechanisms on reduction in mechanical properties of GFRC (after Bentur[3)])

Type of Fiber	Aging Period	Effect of Aging Mechanism on Reduction in Mechanical properties	
		Chemical Degradation of Fibers	Growth of Hydration Products
E-Glass	Short (<1 year)	Very Effective	Mildly Effective
AR-Glass	Short (<1 year)	Not Effective	Not Effective
	Medium (5-40 years)	Mildly Effective	Very Effective
	Long (>30-50 years)	Effective	Very Effective

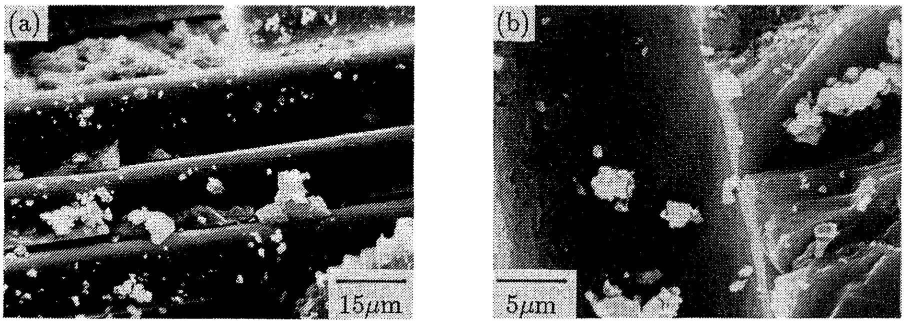


Photo 7 Fracture surface of 1 year old specimens stored in water ; (a) smooth surfaces of glass filaments (b) deposition of $Ca(OH)_2$ at the interface.

4.CONCLUSIONS

GFR concrete is a promising composite applicable to concrete structures in the construction field if the durability problem could be solved. In order to elucidate the mechanisms of durability of GFR concretes, the effects of the storage conditions and the filamentization of the glass fiber strand on the durability of GFR concretes produced by premixing were investigated. Major results obtained in this study are summarized as follows;

(1) Strength, toughness and the resistibility against impact load of GFR concretes produced by premixing decreased with time. Particularly, the reduction in toughness with time was considerably significant.

(2)The effect of storage condition on the degradation in mechanical properties of GFR concrete was not explicitly shown. The reduction in toughness of GFR concretes was found to be inhibited during the period from 3 to 12 months under a dry atmosphere. However, all specimens of GFR concrete fractured in brittle manner at the age of 3 years, regardless of the storage environments.

(3) Relatively rapid progress of age-embrittlement of GFR concretes could not be delayed even when a specific size in the glass fiber strands was used to minimize loosening and separation of strands.

(4) SEM examination revealed that hydration products deposited on the surfaces of glass fibers increased with time. This increase in the amount of hydration products suggested the increase of bond strength of glass fibers to the matrix.

(5) Physical damage of glass fibers due to premixing seemed to lead to the decrease of tensile strength of filaments within the composites. However, sufficient strength as a reinforcement was retained in such a damaged filament.

(6) Loosening and separation of the glass fiber strands were inevitable in the process of premixing, resulting in easy deposition of hydration products in the vicinity of filaments. Therefore, rapid densification in the matrix at the interfacial zone around dispersed filaments may be responsible for the early degradation of GFR concretes.

(7) The integrity and dispersion of glass fiber strand in GFR concretes are greatly different from those in GRC produced by the spray method. These differences significantly affect the time-dependent changes in mechanical properties of the composites.

ACKNOWLEDGEMENT

The authors wish to thank Prof. Fujii, Department of Civil Engineering, Kyoto University for his valuable comments.

REFERENCES

[1] Okada, K., Mise, T, Mashima, M. and Ideguchi, T. : Consistency and mechanical properties on glass fiber reinforced concrete, Proceedings of JSCE, No.343, pp.189-198, 1984 (in Japanese)

[2] Litherland, K.L. and Proctor, B.A. : The effect of matrix formulation, fiber content, and fiber composition on the durability of glass fiber reinforced concrete, Proc. of Durability of Glass Fiber Reinforced Concrete, Symposium, P.C.I., pp.124-135, 1985.

[3] Bentur, A. :Mechanisms of potential embrittlement and strength loss of glass fiber reinforced cement composites, Proc. Durability of Glass Fiber Reinforced Concrete Symposium, P.C.I., pp.109-123, 1985.

[4] Diamond, S. :The GFRC durability problem : nature, characteristics and test method, Proc.

Durability of Glass Fiber Reinforced Concrete Symposium, P.C.I., pp.199-209, 1985.

[5] ARFIBRE, ASAHI GLASS Co.Ltd., 1985.

[6] Leonard, S. and Bentur A. : Improvement of the durability of glass fiber reinforced cement using blended matrix, Cement and Concrete Research, Vol.14, pp.717-728, 1984.

[7] Bentur, A. : Silica fume treatments as a means for improving the durability of glass fiber reinforced concretes, J. ASCE, Materials in Civil Engineering, Vol.1, No.3, pp.167-183, 1989.

[8] West, J.M., De Vekey, R.C. and Majumdar, A.J. : Acrylic-polymer modified GRC, Composites, 16, pp.33-38, 1985.

[9] Marsh, H.N. and Clarke, L.L :Glass fiber reinforced cement base materials, ACI Publication SP-44, pp.247-265, 1974.

[10] Takagi, J. :Some properties of glass fiber reinforced concrete, ACI Publication SP-44, pp.93 -111, 1974.

[11] Mashima, M. : Characteristics of glass fiber reinforced concrete and its application to pavement, 1984.

[12] Specification for design and construction in concretes, Japan Society of Civil Engineers, pp.46-50, 1991 (in Japanese).

[13] Specification for design and construction in the steel fiber reinforced concretes, Concrete Library, Vol.50, Japan Society of Civil Engineers, 1983 (in Japanese).

[14] Igarashi, S., Torii, K., and Hasaba, S. : Impact load resistibility and durability of polymer fiber reinforced concrete, CAJ Review of the 39th General Meeting, pp.364-367, 1986.

[15] Majumdar, A.J., Singh, B., Langley, A.A. and Ali, M.A. :The durability of glass fibre cement - the effect of fibre length and content, Journal of Material Science, 15, pp.1085-1096, 1980.

[16] West, J. M. and Majumdar, A. J. : Strength of glass fibers in cement environments, Journal of Materials Science Letters, 1, pp.214-216, 1982.

[17] Nair, N. G. : Mechanics of glass fiber reinforced cement, Fiber Reinforced Cement and Concrete, Proc. RILEM Symp., The Construction Press., UK, pp.81-93, 1975.

[18] State-of-the-Art Report on Fiber Reinforced Cementitious Composites, JCI, pp.12-15, 1986 (in Japanese).

[19] Proctor, B.A., The development and technology of AR fibers for cement reinforcement, Proc. Durability of Glass Fiber Reinforced Concrete Symposium, P.C.I., pp.64-77, 1985.

[20] Bentur, A., Ben-Bassat, M. and Schneider, D. : Durability of glass fiber reinforced cements with different alkali resistant glass fibres, Journal of American Ceramic Society, 68[4], pp. 203-208, 1985.

[21] Proctor, B. A., Oakley, D. R. and Litherland, K. L. : Development in the assessment and performance of GRC over 10 years, Composites, 13, pp.173-179, 1982.

[22] Mecholsky Jun, J.J.,Freiman, S.W. and Rice, R.W. : Fracture surface analysis of ceramics, Journal of Materials Science, 11, pp.1310-1319, 1976.

[23] Jaras, A. C. and Norman, B. J. : The measurement of glass fiber strength in composites

from studies of their fracture surfaces, Journal of Materials Science, pp.2459-2465, 1983.

[24] Cohen, E.B. and Diamond, S. : Validity of flexural strength reduction as an indication of alkali attack on glass in fiber reinforced cement composites, Proc. RILEM Symp. Fiber Reinforced Cement and Concrete, pp.315-325, 1975.

[25] Franke, L. and Overbeck, E. : Loss in strength and damage to glass fiber in alkaline solutions and cement extracts, Durab. Bldg. Mat., 5, pp.73- 79, 1987.