5 PROPERTIES OF GRC USING RECYCLED MATERIAL

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SUMMARY: Industrial wastes are actively recycled due to the rise of environmental concerns and the processing problem of waste in recent years. This paper describes the research on basic physical properties and durability of GRC when recycled materials, which are widely used as an admixture for concrete, are added. We obtained the results that the durability of GRC is improved by using fly ash, slag and silica fume. On the basis of these results, high-durability GRC mix proportions combined with recycled materials are presented. The bending strengths, after accelerated aging estimated to be equivalent to about 10 years of outdoor exposure in Japan, are higher than initial strengths, which are equal to conventional GRC, because of consuming $Ca(OH)_2$ in the matrix by pozzolanic reactions. No $Ca(OH)_2$ is detected in hardened mortar containing slag and silica fume after accelerated aging by differential thermal analysis and X-ray diffraction analysis.
KEYWORDS: Eco-cement, fly ash, glass fiber, granulated blastfurnace slag, GRC, pozzolanic reaction, recycled material, silica fume.

INTRODUCTION

Industrial wastes are actively recycled due to the rise of environmental concerns and the processing problems of waste in recent years. The importance of utilizing a recycled material as an admixture material for concrete has attracted a growing interest. Large amounts of fly ash and slag are used for concrete, and many research papers have been presented. GRC is widely used for its lightness and excellent form as a building material. However, little research, especially on fly ash and slag, which are popular recycled material in the concrete field, is seen as research related to GRC using industrial wastes. There is only the recent research work on GRC that uses the lightweight aggregate manufactured from waste[(1)]. It is therefore necessary to understand first the basic physical properties and durability of GRC using each recycled material. Some recycled materials are characteristic of excellent pozzolanic reactivity, so there is the possibility to improve durability of GRC by pozzolanic materials. In this work, the properties of fresh GRC, strength and durability were investigated. In particular, the main purpose of this work is to improve durability of GRC by utilizing recycled pozzolanic materials.

MATERIALS AND METHODS

Materials

Table 1 shows recycled materials used for GRC in these experiments. Tables 2 and 3 show characteristics of each recycled material and its chemical composition. Eco-cement, fly ash and granulated blast furnace slag according to Japanese Industrial Standard (JIS) were used. The other materials used for GRC are shown in Table 4. Two kinds of slag were prepared for examining the difference of specific surface area. Four kinds of glass fiber were prepared according to production methods or purpose for each experiment.

Table 1 - Recycled materials

Material	Raw material	Symbol
Eco-cement	Municipal solid waste ash	[EC]
Fly ash	Coal ash	[FA]
Silica fume	Ferro silicon	[SF]
Slag	Granulated blast furnace slag	[SL]

Table 2 - Specific gravity, specific surface area and chemical components of eco-cement

Specific gravity	Specific surface area(cm^2/g)	Cl^-	Ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O
3.17	4300	0.048	1.33	17.8	7.2	4.1	61.1	1.8	3.9	0.3

Ignition loss, xxx

Table 3 - Specific gravity, specific surface area and chemical components of fly ash, silica fume and granulated blast furnace slag

Material	Grade	Specific gravity	Specific surface area (cm^2/g)	Averaged particle size (µm)	SiO_2	Al_2O_3	FeO	CaO	MgO
Fly ash	–	2.2	3890	–	52	33	4	3	1
Silica fume	–	2.2	200000	0.15	96	–	–	–	–
Slag	4000[SL(4)]	2.9	4190	–	34	15	–	42	6
	8000[SL(8)]		7650						

Table 4 - Materials

Material	Type of material	Symbol
Cement	Ordinary Portland cement	[OPC]
Aggregate	Silica sand no. 5	[S]
Air-entraining and high-range water-reducing admixture	Polycarboxylic acid ether	[AEHR]
AR glass fiber	Chopped strand ACS19PH-901X (length = 19 mm)	[GF1]
	Chopped strand ACS25PH-901X (length = 25 mm)	[GF2]
	Continuous roving AR2500H-103(2500tex)	[GF3]
	continuous roving AR2500H-200(2500tex)	[GF4]

Tex, g/1000m

Mixing

An Omni mixer of 30-litre capacity was used for mixing. Silica fume was dispersed in water with an air-entraining and high-range water-reducing admixture **(AEHR)**. This mixture, aggregate, admixture and cement were cast into the mixer and mixed for 60 seconds. In the premix method, AR glass fiber chopped strand was mixed with mortar for 15 seconds. Specimens used for the bending test were obtained by casting the mixed GRC mortar into a mould. In the spray method, the 31mm-long AR glass fiber fiber, cut from continuous roving, and mortar, were sprayed on a mould at the same time.

Density and air content

Fresh and air-dried specific gravities were calculated from volume and weight; the former was obtained by measuring a fresh mortar and the latter was obtained by measuring specimens for the bending test at the age of 28 days.

Air content was measured by using the pressure method provided in JIS A 1128.

GRC flow value

A GRC flow value of fresh GRC mortar (including glass fiber) was measured by flow test of the physical testing method for cement provided in JIS A 5201. A flow cone of 70mm upper diameter, 100mm lower diameter and 70mm high was placed on a flow table. It was filled with fresh GRC mortar and pulled straight up. The GRC mortar was given a 10mm dropping movement 15 times in 15 seconds by rotating handle. The diameter of flowed GRC mortar was measured as a GRC flow value.

Bending test

Bending strength, strain to failure and modulus of elasticity were measured by the bending test prescribed by the Japan GRC Association, test conditions of which are shown in Table 5. Specimens for the bending test were demoulded at the age of one day and stored in a curing room at 20°C, 60% relative humidity (RH) until the age of 28 days.

Table 5 - Bending test conditions

Production method	Dimensions of specimen (mm)	Bending span (mm)	Test speed (mm/min)	Loading method
Premix	275 × 50 × 15	225	2	3-point
Spray	250 × 50 × 10	200	5	

Accelerated aging test
The accelerated aging test was conducted by immersing specimens in water at 70°C after curing at 20°C, 60% RH for 28 days. The durability of GRC was evaluated by the bending test after the accelerated aging test. It is said that bending strength of GRC after one day of immersion in water at 70°C is estimated to be equivalent to about one year of outdoor exposure in Tokyo(2).

Differential thermal analysis and X-ray diffraction analysis of hardened mortar
Mortar specimens (not including glass fiber) were immersed in water at 70°C for 10 days after curing at 20°C, 65% RH for 28 days for differential thermal analysis (DTA) and X-ray diffraction analysis (XRDA). Accelerated specimens were dried and powdered; after that they were analyzed by DTA on condition that heating speed was 10°C/minute in circulating air. The same specimens used for DTA were analyzed by XRDA on condition that range of diffraction was from zero to 60 degrees.

Mix proportions
Base mix proportions of GRC are shown in Table 6. Experiments in this paper consist of three parts. Both the first and second parts were conducted by the premix method; on the basis of these results, the third part was conducted by the spray method. The water/binder ratio and sand/binder ratio were not changed because they affect bending strength. Recycled materials were incorporated into mix proportions by replacement of cement and as an additive. **AEHR**/binder ratio was adjusted to make a flow value of GRC mortar of about 150mm.

Table 6 - Base mix proportions

Part	Production method	W/B	S/B	**AEHR** (wt.% against binder)	Type of glass fiber	Fiber content (wt.% against mortar)
First	Premix	0.32	1.0	0.6–1.3	19mm-long chopped strands	3
Second				0.5–1.0	25mm-long chopped strands	
Third	Spray			0.7	2500tex roving	5

W, water; S, sand; B, binder (cement, fly ash, slag)

RESULTS AND DISCUSSION

First part of the experiment

Properties of fresh GRC mortar
Mix proportions, properties of fresh GRC and air-dried specific gravity in the first part of the experiments are shown in Table 7.

The properties of fresh GRC with 100% replacement of cement by eco-cement were almost the same when compared with that of fresh conventional GRC.

The specific gravity of fresh GRC mortar should decrease if a large proportion of cement is replaced by fly ash, because specific gravity of fly ash is lower than that of ordinary cement, but a change of the fresh specific gravity in this experiment was not shown by a reduction of air content with the influence of non-combustion carbon in fly ash. On the other hand, air-dried specific gravity decreased with increasing the proportion of fly ash.

Fresh GRC mortar containing silica fume needed a greater amount of **AEHR** in order to keep flowability. But the air content of fresh GRC mortar containing silica fume was reduced in spite of increasing the amount of **AEHR**. It seems that the large specific surface area of silica fume affected air content greatly.

Flowability of fresh GRC mortar containing granulated blast furnace slag was improved with increasing the proportion of the slag, so the amount of **AEHR** could reduce to 0.4. But the air content of GRC containing grade 4000 slag **(SL(4))**, the specific surface area of which was larger than that of grade 8000 slag **(SL(8))**, reduced. These show that the specific surface area of the material is one of the important factors affecting air content.

Table 7 - Mix proportions, properties of fresh GRC and air-dried specific gravity

No.	1	2	3	4	5	6	7	8	9	10	11	12	13
C	100		80	60	40	100	100	80	60	40	80	60	40
EC		100											
FA			20	40	60								
SL (4)								20	40	60			
SL (8)											20	40	60
SF						10	20						
S	100	100	100	100	100	100	100	100	100	100	100	100	100
R	0.6	0.6	0.6	0.6	0.6	0.8	1.3	0.4	0.4	0.4	0.4	0.4	0.4
W	32	32	32	32	32	32	32	32	32	32	32	32	32
GF1	7.0	7.0	7.0	7.0	7.0	7.3	7.6	7.0	7.0	7.0	7.0	7.0	7.0
Fresh specific gravity	2.07	2.09	2.07	2.07	2.07	2.12	2.15	2.11	2.10	2.06	2.12	2.14	2.10
Air-dried specific gravity	2.05	2.11	2.01	1.98	1.95	2.03	2.05	2.07	2.03	2.03	2.06	2.04	2.06
Air content (%)	8.0	9.4	7.4	6.4	4.5	6.4	5.6	8.2	8.4	8.4	8.4	7.6	6.5
GRC flow value (mm	161	155	172	160	150	155	153	150	163	175	155	158	165

Bending characteristics at early ages

Bending characteristics at early ages are defined as those at the age of 28 days in this paper. Figure 1 shows the results of the bending test of GRC using recycled materials at early ages.

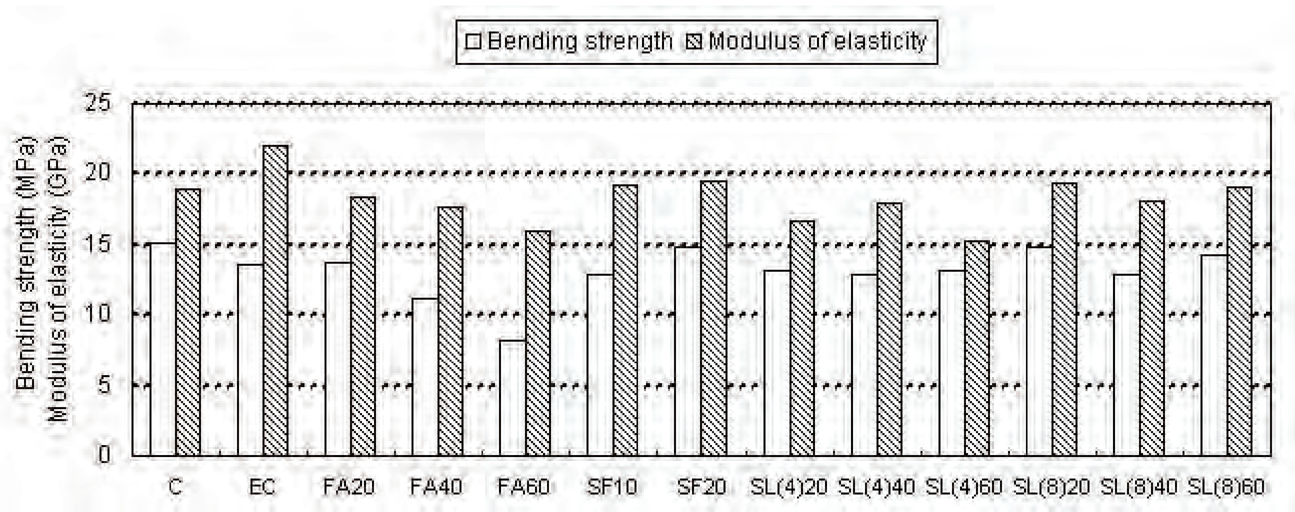

Figure 1 - Bending strength and modulus of elasticity at early ages

There was no significant difference in bending characteristics between ordinary Portland cement and eco-cement.

Both bending strength and modulus of elasticity of GRC containing fly ash decreased with increasing the proportion of fly ash. Bending strength of GRC with 60% replacement of cement by fly ash decreased to about half as strong as that of conventional GRC. The evidence that early strength of the matrix was incomplete can be seen in the reduction of the modulus of elasticity.

The addition of silica fume indicated no definite tendency on bending characteristic.

Bending strengths of GRC containing the slag decreased as a whole in comparison with that of conventional GRC. There was no definite tendency depending on the proportion of slag. But bending strength and modulus of elasticity of GRC containing **SL(8)** were high compared with **SL(4)**. This shows that the pozzolanic reaction of slag is improved by an increase of specific surface area.

Bending durability
Bending strengths measured at early ages and after immersion in 70°C water for 10 days are shown in Figure 2.

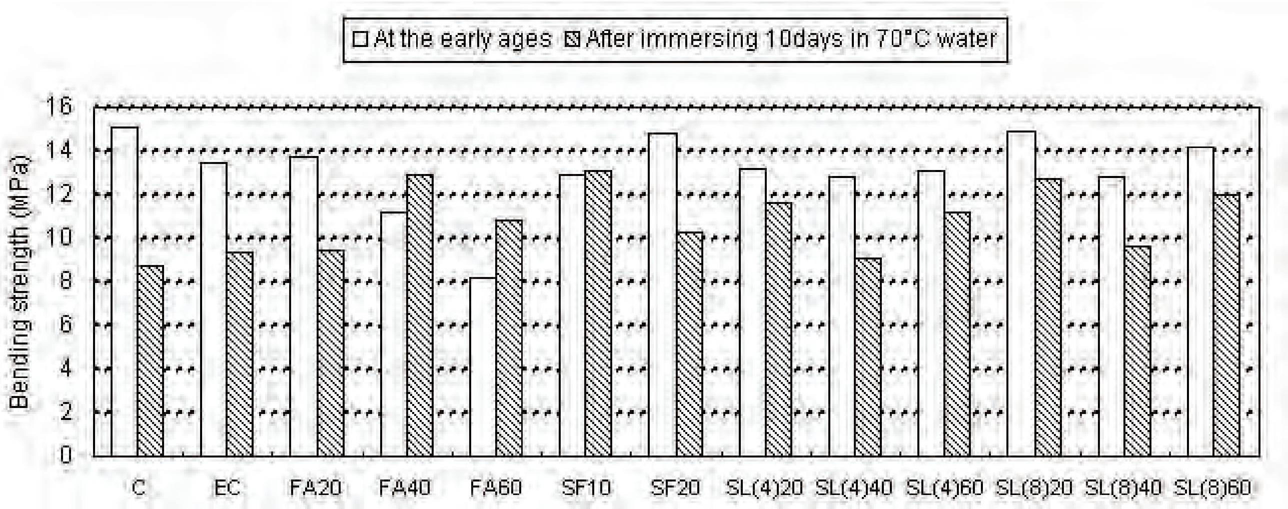

Figure 2 - Bending strengths before and after accelerated aging

Bending strengths of GRC using eco-cement and ordinary Portland cement after accelerated aging were almost the same. The bending strength of GRC containing fly ash after accelerated aging showed a tendency to reduce according to the proportion of fly ash. For GRC with more than 40% replacement of cement by fly ash, the bending strength after accelerated aging was higher than that at early ages.

There was no definite trend of bending strength depending on the proportion of the slag or the amount of silica fume added. But the bending strength of GRC containing slag or silica fume after accelerated aging was higher than that of conventional GRC; also, the bending strength of GRC containing **SL(8)** was higher than that of GRC containing **SL(4)**, including the results at early ages.

It can therefore be considered that there are improvements of durability by pozzolanic reactions of fly ash, slag and silica fume in GRC as well as in concrete.

Second part of the experiment

Properties of fresh GRC mortar
On the basis of the results in the first part of the experiments, the combinations of fly ash, slag and silica fume, which bring about the pozzolanic reaction with the cement matrix, are examined with the purpose to improve the early strength of GRC in the second part of the experiments.

Mix proportions, properties of fresh GRC and air-dried specific gravity are shown in Table 8.

The following results in the second part of the experiment indicate some tendencies of each recycled material to be similar to those in the first part of the experiments.

- The addition of silica fume to GRC leads to a reduction of air content and flowability.
- The replacement of cement by slag in GRC improves flowability.
- The replacement of cement by fly ash in GRC leads to reductions of air content, flowability and air-dried specific gravity.

Table 8 - Mix proportions, properties of fresh GRC and air-dried specific gravity

No.	14	15	16	17	18	19
C	100	50	40	30	30	30
FA						70
SL (4)		50	60	70	70	
SF	-	10	10	10	5	10
S	100	100	100	100	100	100
R	0.7	0.7	0.7	0.7	0.5	1.0
W	32	32	32	32	32	32
GF2	7.0	7.3	7.3	7.3	7.1	7.3
Fresh specific gravity	2.22	2.18	2.20	2.19	2.14	2.07
Air-dried specific gravity	2.13	2.15	2.14	2.13	2.11	1.92
Air content (%)	6.3	5.5	5.4	5.4	5.7	3.0
GRC flow value (mm)	179	164	166	173	168	160

Bending characteristics

Figures 3 and 4 show the results of the bending test after accelerated aging by immersion in 70°C water. More than 5% addition of silica fume improved the initial bending characteristics of GRC with cement replaced cement by slag up to 70% against cement weight. Especially, the bending strength of GRC with cement replaced by slag at 70% and added silica fume at 10% against cement weight after immersion in 70°C water for 10 days indicated no reduction compared with that before accelerated aging.

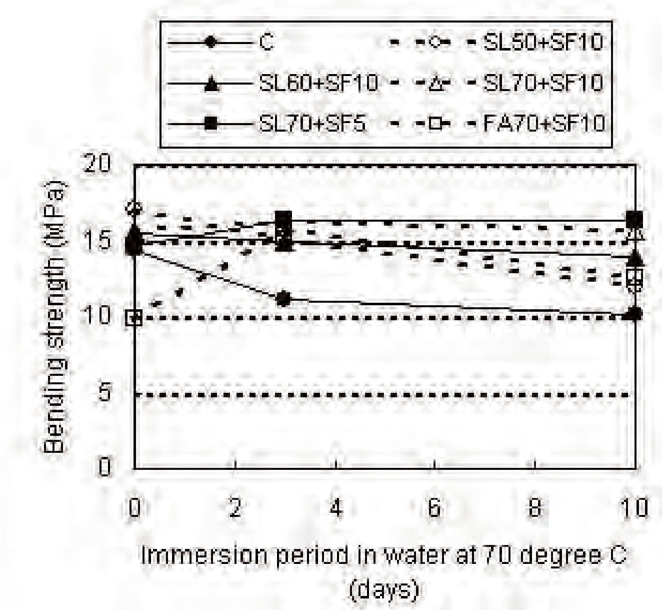

Figure 3 - Bending strength

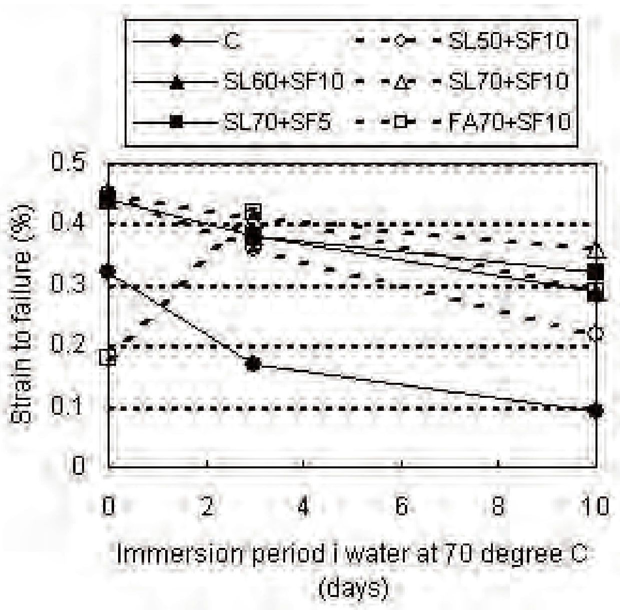

Figure 4 - Strain to failure

Bending characteristics after accelerated aging were also improved according to the proportion of slag. Bending characteristics of GRC combining fly ash and silica fume at the early ages were inferior to those combining slag and silica fume, but durability was almost the same for either. Fly ash, slag and silica fume used in this experiment as a recycled material are pozzolans. It is said that the reactivity of pozzolan in amorphous state with larger specific surface area and higher basicity is better. It seems that the reactivity of silica fume with the largest specific surface area as 200,000cm^2/g is superior to that of slag or fly ash. So it is assumed that silica fume has reacted with $Ca(OH)_2$ produced during hydration of the cement in the early stage and then slag or fly ash has reacted with $Ca(OH)_2$. Such a continuous pozzolanic reaction with $Ca(OH)_2$ for a long time leads to improvement of durability for GRC by keeping a suitable bonding state between glass fiber and matrix. In GRC, the bonding strength between fiber and matrix depends on the degree of hydration of cement. A weak bonding strength is caused by reduction of matrix strength. By contrast, a strong bonding strength makes fiber break before being pulled out of the matrix, and causes the reductions of strain to failure and bending strength. So in the case of using fiber with high elasticity as in AR glass fiber, it is important to keep a suitable bonding state between fiber and matrix and to make the fiber pull out of the matrix by a suitable stress(3).

Third part of the experiment

Figures 5 and 6 show the results of the bending test of GRC made by the spray method in the third part of the experiment and then mix proportions obtained from the results of the second part of the experiment are shown in Table 9.

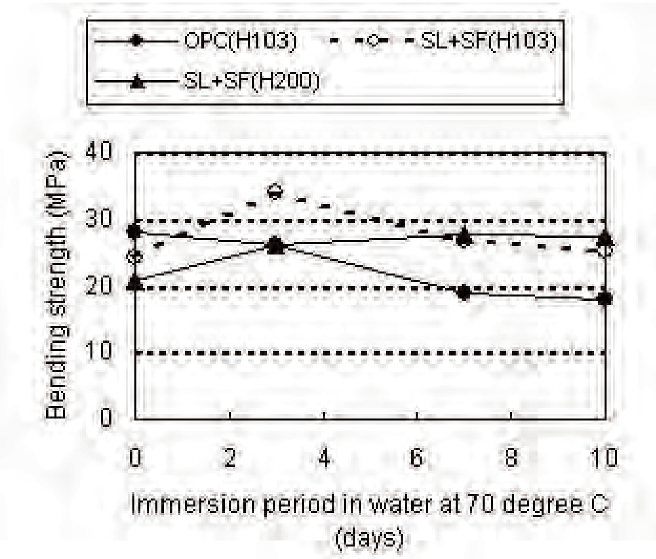

Figure 5 - Bending strength

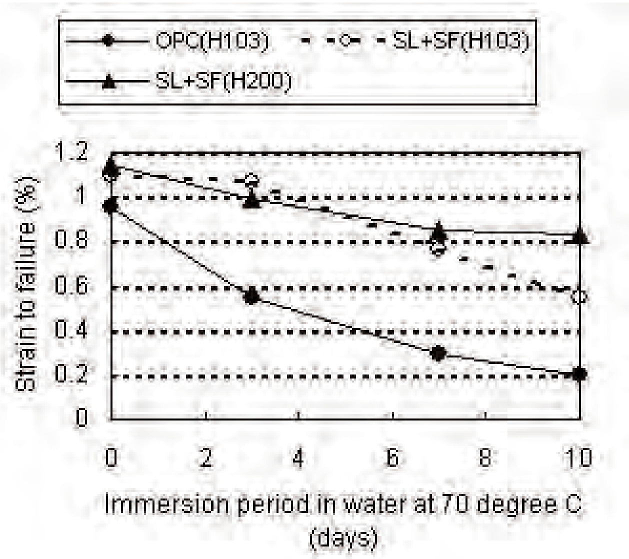

Figure 6 - Strain to failure

Table 9 - Mix proportions and air-dried specific gravity

No.	20	21	22
C	100	30	30
SL (4)		70	70
SF		10	10
S	100	100	100
R	0.7	0.7	0.7
W	32	32	32
GF	GF3	GF3	GF4
Air-dried specific gravity	2.13	2.13	1.92

Early bending strength of GRC with 70% replacement of cement by slag and 10% addition of silica fume was almost the same as that of conventional GRC. The bending durability of GRC containing slag and silica fume after immersion in 70°C water for 10 days was greatly improved compared with conventional GRC, in that the retention of strain to failure was more than 50%. There was a significant difference of durability in different kinds of roving. The durability of GRC using H200 roving as a highly durable roving is superior to that using H103 roving as a conventional roving. As a result, the value of strain to failure of GRC combining slag, silica fume and the high-durability roving after immersion in 70°C water for 10 days could be kept at more than 0.8%.

DTA of hardened mortar

Figure 7 shows the results of DTA of hardened mortar used for the third part of the experiment. The presence of $Ca(OH)_2$ in mortar made of ordinary Portland cement after accelerated aging was revealed by an endothermal peak around 440°C. But there was no peak of $Ca(OH)_2$ in mortar made of slag and silica fume at a similar temperature.

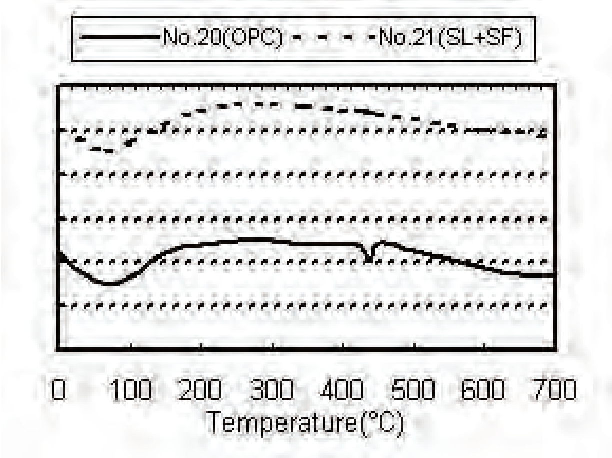

Figure 7 - DTA of hardened mortar

XRDA of hardened mortar

Figures 8 and 9 show the results of XRDA of hardened mortar. A comparison of two diffraction patterns revealed a significant change due to the presence of pozzolans. A peak of $Ca(OH)_2$ at 17.9° was present in the diffraction pattern of mortar made from ordinary Portland cement, but there was no peak in the diffraction pattern of mortar containing slag and silica fume. The presence of $Ca(OH)_2$ in a matrix combining slag and silica fume after accelerated aging could not be confirmed by XRDA as well as DTA. This result indicates that slag and silica fume consume $Ca(OH)_2$ produced during hydration of cement in matrix by pozzolanic reactions and this leads to the good durability of GRC.

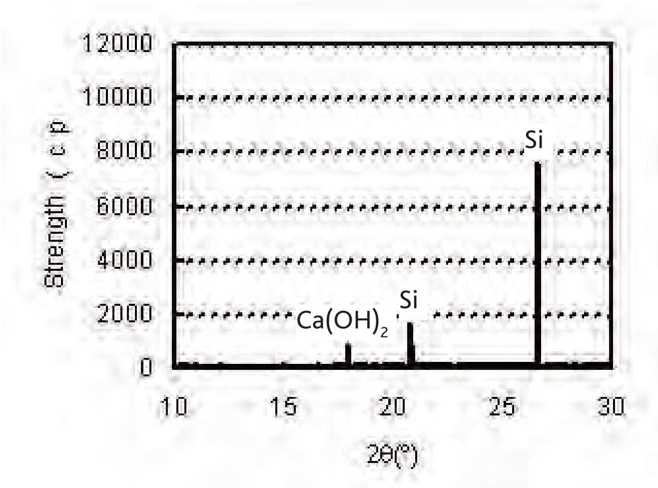

Figure 8 - XRDA of hardened mortar (No. 20: OPC)

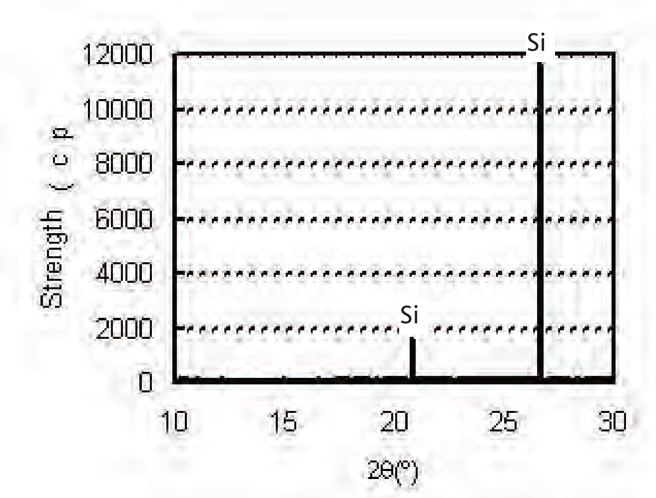

Figure 9 - XRDA of hardened mortar (No. 21: SL+SF)

CONCLUSIONS

- The properties of premix GRC using eco-cement are quite similar to those that used ordinary Portland cement.
- The replacement of cement by fly ash in premix GRC reduces air content, flowability and initial bending strength, and improves durability.
- The addition of silica fume in premix GRC reduces air content and flowability, and improves durability.
- Replacement of cement by granulated blast furnace slag in premix GRC reduces initial bending strength, and improves flowability and durability. The durability of GRC replaced by slag improves according to its replacement rate.
- Early bending strength of premix GRC with cement replaced by slag is improved to the same as that of conventional GRC by more than 5% silica fume addition, but there is no effect of silica fume addition on early bending strength of GRC with cement replaced by fly ash.
- After accelerated aging corresponding to about 10 years of outdoor exposure in Japan, no reduction in either bending strength or strain to failure is apparent for premix GRC with 70% replacement of cement by slag and 10% silica fume addition.
- For spray GRC with the above mix proportions after accelerated aging, there is no reduction in bending strength and the value of strain to failure can be kept at more than 0.8%.
- No $Ca(OH)_2$ is detected in hardened mortar containing slag and silica fume after accelerated aging by DTA and XRDA.
- In the case of using fiber with high elasticity such as AR glass fiber, it is important to keep a suitable bonding state between the glass fiber and the matrix.

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