A STUDY ON MIX PROPORTIONS AND PROPERTIES OF STEEL FIBER REINFORCED ROLLER-COMPACTED CONCRETE FOR PAVEMENTS

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Indented and hooked steel fibers were selected as two possibilities for use in roller-compacted concrete for pavements. Appropriate unit water content, sand percentage, and fiber content were determined while water was reduced by a suitable degree by incorporating a superplasticizer in appropriate proportion. The target consistency was given in terms of a vibration compaction value as measured by a Swedish-type Vebe apparatus. Segregation was reduced by using steel fibers, and the fiber orientation in the concrete tended to approach the horizontal when compaction was with a surface vibrator. Flexural strength, ductility, and frost resistance were improved. Bond strength between the concrete and abraded asphalt pavement surface were evaluated at the age of 7 days. Drying shrinkage was almost the same as for non-fiber roller-compacted concrete despite the increase in unit water content for a given consistency.

Keywords: *mix proportion, degree of segregation, fiber orientation, flexural strength, flexural ductility, frost resistance, drying shrinkage*

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1. INTRODUCTION

Roller-compacted concrete for pavements (RCCP) suffers from a number of problems. In particular, the use of tie bars or slip bars is difficult, because of the heavy compaction by vibratory roller. As a result, it is known that RCCP is prone to cracking due to thermal stress or drying shrinkage, and this prevents the placing of pavement slabs with long joint spacing. On the other hand, steel-fiber reinforced concrete (SFRC) has been used for tunnel linings and bridge deck strengthening, where it offers superior flexural strength and crack resistance, and the strengthening effect of SFRC has been looked over again from a view point of compound materials. If roller-compacted concrete (RCC) could be given the properties of SFRC, it would offer advantages as a heavy traffic pavement because of its rapid construction and shorter lead time. There is good reason, therefore, to accumulate basic data on the properties of such a new type of pavement.

Ficheroulle[1)] indicated that one could lay pavement with steel-fiber-roller-compacted concrete (SFRCC) containing 30mm corn type steel fibers as easily as with conventional RCC. From the results of observations, it was clarified that the surface texture of the pavement could secured by paving with a thin layer of asphalt without joints and that traffic noise was reduced. This method proved suitable for heavy traffic. However, details of mix proportion and the mechanical and physical properties of the SFRCC were not described in the report. Nanni et al.[2)] carried out trial pavement construction with SFRCC containing 0.6 wt% of straight and hooked steel fibers (30 mm in length). They described how construction could be carried out appropriately, and demonstrated that strength and toughness were improved. However, accumulation of experimental results with various fiber contents was still needed. In Japan, there has been little research with SFRCC, and data on mix proportions and the properties of fresh and hardened SFRCC are needed before it can be applied to actual pavements.

In this study, four types of steel fiber are tested from the viewpoint of reinforcement effect. These are indented and hooked steel fibers with different lengths. The first step in the study was to decide on the mix proportion. The relation between water content and modified VC value as a consistency reading was obtained, and a unit water content and sand percentage for a given consistency were decided. Then relations between fiber content and both modified VC value and flexural strength were obtained, and appropriate fiber contents were decided from the viewpoints of workability and strength. The degree of unit water content reduction and the resulting change in flexural strength when a superplastcizer was added were examined, and an appropriate dosage selected.
Secondly, the degree of coarse aggregate segregation and steel fiber segregation was clarified using drop test apparatus. Then the angle of the steel fibers in the SFRCC to the horizontal after compacting by surface vibrator was measured, and the angle was compared with the case of compacting by an immersed vibrator.

Thirdly, the mechanical properties of the concrete were investigated, and differences in flexural strength and toughness depending on fiber type were clarified. Then, assuming that SFRCC would be overlaid on the abraded asphalt pavement surface, the bond strength between the concrete and asphalt was tested.

Finally the physical properties of the SFRC were investigated. The freezing and thawing resistance with and without AE agent was compared, and drying shrinkage properties were examined for each fiber type. A number of useful results were obtained from these investigations.

2. EXPERIMENTAL OUTLINE

(1) Materials and Mix Proportions

Normal Portland cement (density: 3.16g/cm^3), river sand (density: 2.54g/cm^3; absorption: 3.46%; FM: 2.74), crushed stone (density: 2.67g/cm^3; absorption: 1.46%; FM: 6.60), an AE water reducing agent (retarder type; lignin sulfonic acid compound), a superplasticizer (AE type; polycarbonate acid compound), an AE agent (natural reginate), and a supplementary AE agent (degenerated alkilcarbonate acid compound) were used. All agents were used in the form of undiluted solution or solution, and they were combined with the water.

Table 1 Shape and size of steel fibers

Symbol	Gravity	Length (mm)	Diameter (mm)	Aspect ratio	Type
I-1	7.85	50	0.7	71	Indented
I-2		30	0.6	50	
F-1		60	0.8	75	Hooked
F-2		30	0.6	50	

Table 2 Mix proportions of concrete

No.	Modified VC value (sec)	Void ratio (%)	Air content (%)	Water-Cement ratio (%)	Sand percentage (%)	Steel Fiber content (vol%)	Unit weight (kg/m^3)						Type of Fiber
							Water	Cement	Sand	Gravel	Steel Fiber	Admixture*	
1	38～82	0.1～2.7	2.3～3.6	37.0～41.2	41.8	－	107～119	289	845～858	1236～1255	－	0.72	－
2	21～60	0.3～3.3	1.7～3.4	39.8～46.7	42.0	1.0	115～135	289	821～842	1191～1222	79	0.72	F-2
3	50～273	0.8～8.4	0.8～6.1	39.8	30～60	1.0	116	289	597～1203	843～1476	79	0.72	F-1,2 I-1,2
4	21～285	0.3～8.1	2.6～3.9	39.8	40.0	0～1.6	116	289	791～806	1256～1281	0～118	0.72	F-1,2 I-1,2
5	53	0.1	2.3	37.0	40.0	－	107	289	811	1294	－	0.72	－
6	46	0.5	2.1	42.6	40.0	1.0	123	289	785	1252	79	0.72	I-1
7	51	0.6	2.7	40.5	40.0	1.0	117	289	791	1261	79	0.72	I-2
8	55	1.0	2.1	41.2	40.0	1.0	119	289	789	1258	79	0.72	F-1
9	47	0.3	2.8	39.4	40.0	1.0	114	289	794	1266	79	0.72	F-2
10	49～53	2.1～3.4	2.4～3.4	34.3～36.0	40.0	1.0	99～104	289	817～822	1296～1308	79	1.45～4.34	－
11	45～51	0.6～2.3	1.8～3.1	39.8～41.9	40.0	1.0	115～121	289	790～799	1256～1266	79	1.45～4.34	I-1
12	46～54	2.0～3.0	2.0～3.6	38.8～39.8	40.0	1.0	112～115	289	796～802	1266～1270	79	1.45～4.34	I-2
13	45～49	2.4～3.8	3.0～4.3	38.1～40.1	40.0	1.0	110～116	289	796～804	1263～1273	79	1.45～4.34	F-1
14	45～55	2.4～3.4	3.0～4.5	36.0～38.4	40.0	1.0	104～111	289	800～810	1271～1282	79	1.45～4.34	F-2
15	53	0.1	3.0	36.3	40.0	－	105	289	816	1298	79	0.72 0.029	－
16	45	0.2	3.5	40.8	40.0	1.0	118	289	793	1260	79	0.72 0.029	I-1
17	48	0.2	4.0	39.8	40.0	1.0	115	289	796	1266	79	0.72 0.029	I-2
18	48	0.3	3.6	40.5	40.0	1.0	117	289	794	1261	79	0.72 0.029	F-1
19	52	0.2	3.7	38.8	40.0	1.0	112	289	799	1270	79	0.72 0.029	F-2
20	8**	-	4.2	40.0	45.5	1.0	185	463	703	892	79	0.14	F-2

*AE water reducer is used in 1～9. Super AE water reducer is used in 10～14. AE water reducer (left side) and assistant AE agent (right side) is used in 15～19

** 20 is conventional SFRC and has 8cm slump

Generally, for good reinforcing effect, fiber length is greater than the maximum size of aggregate and the diameter to length ratio (aspect ratio) is more than 50. However, the aspect ratio should be less than 100 because longer fibers tend to form fiber balls. In this study, two fiber lengths were used. The fiber types, sizes, and aspect ratios are shown in Table 1. The indented fiber has an indented surface and the hooked fiber has hooks at both ends.

Table 2 shows the mix proportions of the concrete used in the experiment. Mix proportions 1 to 4 and 10 to 14 were used to examine the characteristics of SFRCC mix proportions, while mixes 5 to 9 and 15 to 20 were used to examine the degree of segregation, fiber orientation, mechanical characteristics, freezing and thawing resistance, and drying shrinkage.

(2) Manufacture of concrete

To produce SFRCC, the crushed stone, sand, cement, and water (containing the agents) were placed in a pan-type mixer of $0.05m^3$ capacity and mixed for 60 seconds. The fiber was then manually added little by little and mixed for 210 seconds. The total mixing time was therefore four and a half minutes. For conventional RCC, the concrete was mixed for 90 seconds. After mixing, test sample was taken from the concrete and consistency was measured using a Swedish-type VB consistency-meter. Compaction degree was measured after 60 seconds of vibration. The air content was measured after the consistency test using the JIS A 1116 method (gravimetric method) and the JIS A 1128 method (Washington-type air meter). In the case of JIS A 1128, the sample was placed in a vessel in three layers and a rod inserted 25 times. The layers were compacted using a vibrating tamper until liquefied mortar rose up through the space between tamper plate and vessel wall. After compaction, the vessel was fitted with a cap and the air content was measured by opening a pressure valve. The size of test specimen was 10×10×40cm and the concrete was weighed so as to ensure a 96% compaction degree for each sample. The first layer of concrete was placed in the mold, and the rod inserted 25 times. A steel plate was placed on the concrete surface, and then the concrete was compacted using a vibrating tamper (frequency: 50 Hz; weight: 15 kg) until liquefied mortar rose up in the space between plate and mold. Before casting the second layer, the top surface of the first layer was scratched and loosened using a steel rod so as to ensure the integrity of the two layers. The top surface was finished using a steel trowel.

(3) Test Method for Measuring Segregation Degree and Orientation

a) Segregation degree

Segregation of RCC is particularly notable when concrete is discharged from hopper to dump truck and from dump truck to the asphalt finisher at the construction site. The test apparatus was designed to replicate site conditions in the laboratory[3)]. It has a 160cm high and 80cm long vertical chute, and an 80cm diagonal chute at a 45 degrees angle. A vinyl sheet measuring 0.2mm in thickness was placed inside the chutes to provide a smooth surface.

Concrete samples weighing about 10 kg were dropped into the inlet of the vertical chute in a single throw. After discharge from the apparatus, samples were divided equally into one part near the outlet and the remainder. The coarse aggregate and fiber were washed out from each 5 kg sample according to JIS A 1112 (test method for washing analysis). Degree of segregation was calculated by using Eq.1.

$$\text{Segregation degree } Sg\ (\%) = (CA_2 - CA_1)/\ CA_0 \times 100 \qquad \cdots\cdots (1)$$

CA_0 : Ratio of unit coarse aggregate or steel fiber content to unit weight of concrete.

CA_1, CA_2 : Ratio of weight of coarse aggregate or steel fiber in the sample to weight of concrete sample with CA_1 the sample taken near the outlet and CA_2 the other sample.

b) Orientation

Since it was thought that the fiber orientation differed in SFRCC compacted by a surface vibrator and SFRC compacted by an immersed vibrator, the orientation of steel fibers in SFRCC and SFRC specimens was measured. Orientation angle θ ($\theta \leqq 90$ degrees) was defined as the angle of the fiber to the horizontal. In order to measure this angle, the surface paste on one side of an SFRCC specimen was washed out with a water spray 4 or 5 hours after casting. Then, the angle at the surface, which was divided into three blocks for measurement purposes, was measured using a protractor 24 hours later. In the case of SFRC, a super retarder was spread on the side of the rectangular mold so as to allow washing out of the paste. In this case, the paste was washed out 5 or 6 hours after casting and measurements were carried out 24 hours later. There were 20 to 30 fibers in each block of the two specimens (one specimen each for SFRCC and SFRC).

(4) Test Method for Mechanical Properties

a) Flexural strength and toughness test method

Specimens of SFRCC and SFRC were cured in a water bath at 21℃ for 28 days. The flexural strength and toughness of the concrete were measured according to JSCE-G552-1983. Three or four specimens were tested for a given test condition.

b) Bond strength test method

An asphalt specimen was taken from national highway 16 after being in service for several years. The specimen was cut to obtain plates 10 cm in width, 40 cm in length and 5 cm in thickness. These were cured for 2 days in an air bath at 20℃ and 60% relative humidity. The asphalt plates were placed in a mold measuring 40cm in length, 10cm in width and 10cm in depth, and a 5cm layer of SFRCC was placed directly onto the traffic-abraded surface of the asphalt plate. The mold was removed after 24 hours, and then the resulting beam specimens were cured by wrapping in wet cloth in the laboratory. After 1, 3, and 7 days of curing, test specimens were cut out with measurements 10cm width, 10cm height and 15cm length. The loading surface of the specimen was smoothed with a concrete cutter and polisher, and tests were carried out by the splitting tensile test method[4] shown as Fig. 1. An average splitting tensile strength was obtained by testing six specimens.

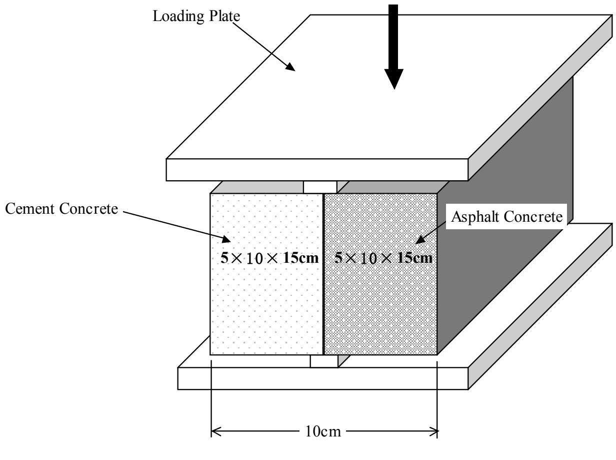

Fig.1 Bonding test specimen and method

(5) Test method for freezing-thawing resistance and drying shrinkage strain

The freezing-thawing test was conducted according to JSCE-G501-1986. The ultrasonic velocity of concrete was measured when the specified number of cycles had been completed. Drying shrinkage strains of the concrete specimens, which were cured in a water bath at 21℃ for 7 days, was measured over 190 days at 20℃ and 60% relative humidity using a contact gage according to JIS A 1129. The percentage weight loss was also measured.

3. EXAMINATION OF MIX PROPORTION CHARACTERISTICS

There have been no previous reports on mix proportions for SFRCC as applied to pavements, but it is thought that the design process basically begins with a decision on unit water content and sand percentage from a viewpoint of good workability, required strength, durability, crack resistance, and other factors.

The purpose of this chapter is to examine differences in mix proportion when steel fibers are used, based on the mix design of conventional roller compacted concrete. To this end, the consistency of the concrete was measured using a Swedish-type Vebe apparatus in terms of a vibrating compaction value (VC value), and then appropriate unit water content, sand percentage and fiber content were determined. The water reducing effect of adding a superplasticizer was also examined. Mix proportions 1 to 4 and 10 to 14 as shown in Table 2 were used in this chapter.

(1) Unit Water Content and Sand Percentage

Figure 2 shows the relationship between unit water content and modified VC value when concrete is mixed with and without steel fiber F-2 as shown in Table 1. Modified VC value tends to decrease as the unit water content increases. The change in modified VC value when the unit water content is above 115kg/m^3 reaches almost 3 to 4 seconds per 1kg/m^3 of unit water content, both with and without steel fibers. These results indicate that it is possible to estimate unit water content, because the change in modified VC value is almost constant for a given shape and size of fiber. In this respect, it is similar to the relationship between unit water content and slump in conventional SFRC.

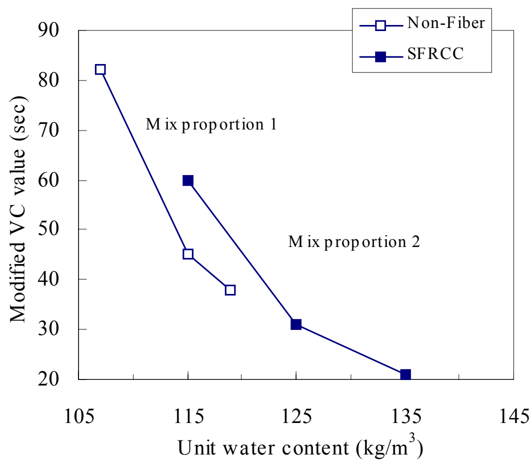

Fig. 2 Changes in modified VC value

Figure 3 shows the relationship between water content of the mix proportions shown in Fig. 2 and flexural strength at the age of 7 days. Flexural strength decreases with rising water-cement ratio because the modified VC value falls with increasing unit water content for a given unit cement content. The water cement ratios ranged from 40% to 47%

and from 37% to 42%, respectively, for the cases with and without steel fibers. The strength difference in the two cases was about 0.7 and 0.5 N/mm2, respectively. The strength of concrete with steel fibers was 1.5 times higher than that without fibers for a given water-cement ratio, so the reinforcing effect of the steel fibers is significant. Thus it is considered that the use of steel fibers is advantageous in terms of early opening to traffic.

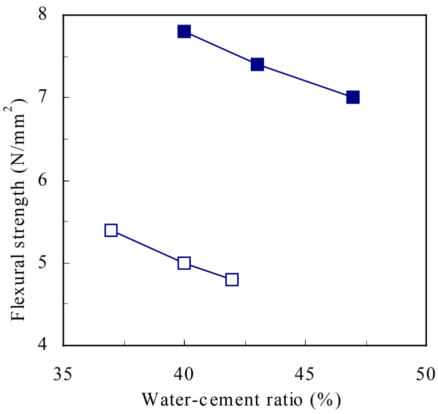

Fig.3 Relationship between water-cement ratio and flexural strength

Generally, unit water content is determined as the minimum possible for a given consistency. Therefore, the sand percentage was selected to suit the minimum unit water content of 115 kg/m^3 for the consistency range of 40 to 60 seconds (modified VC value).

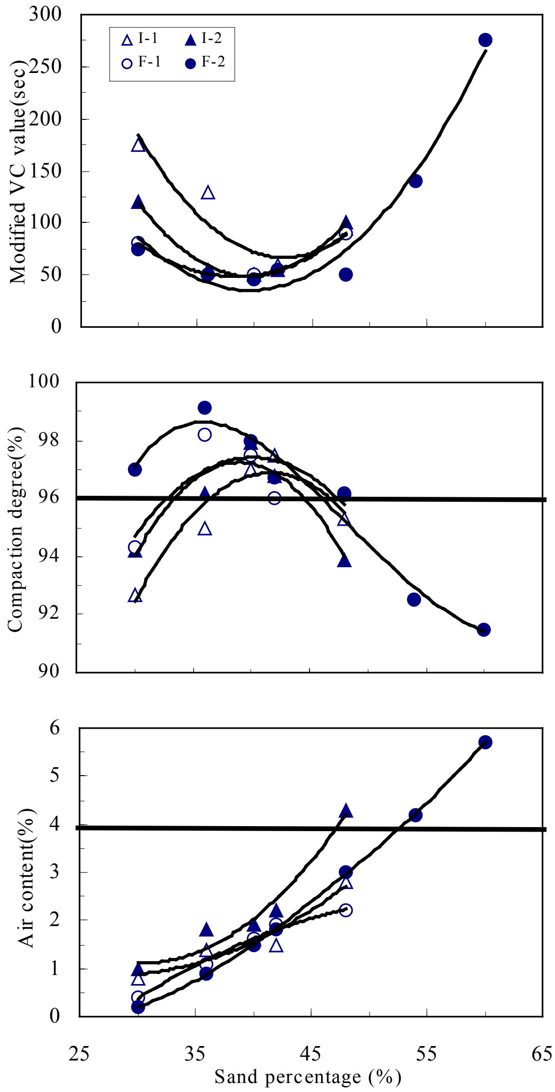

Fig.4 Relationship between sand percentage and modified VC value, compaction degree, and air content

Figure 4 shows the relationship between sand percentage and modified VC value, compaction degree, and air content (as measured by a Washington-type air meter). The reason for use of this type of air meter was the desire to examine the remaining air void content of the concrete, after compacting with a surface vibrator. These graphs clearly show the minimum modified VC value and maximum compaction degree for the given sand percentage. The sand percentage was about 40% independent of steel fiber type. According to one reference[5], these overall tendencies are the same as for conventional RCC and generally, the sufficient compaction degree are given more than 96 % of compaction degree. From this specification, the optimum sand percentage of SFRCC was decided 40 % for a given consistency and compaction degree. The air content increased proportionally with rising sand percentage for a constant unit water content. This is probably due to the lack of sufficient cement paste content to fill the voids formed by the sand particles. Further, it was observed that when the sand percentage exceeded 48% that fibers gathered locally without proper dispersal in the case of I-1, and they remained being combined with water-soluble glue in the case of type F fibers, which were easier to add to the mixer than type I.

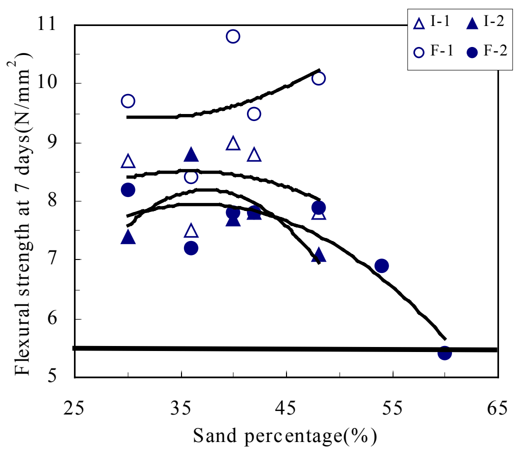

Fig.5 Relationship between sand percentage and flexural strength

Figure 5 shows the relationship between sand percentage and flexural strength at the age of 7 days. The bold line shows strength without steel fibers. It is clear that strength remains almost constant up to a 48% sand percentage and is 1.3 to 1.8 times more than the strength without steel fibers. In case of fiber F-2, the strength decreased drastically beyond 48% sand percentage and was almost the same as in the case without steel fibers. This lack of strengthening effect is explained as follows. The fibers were dispersed insufficiently in the concrete and air voids remained as a result of a shortage of cement paste, even if the concrete was compacted sufficiently. It is concluded that the unit water content should be greater than 115 kg/m^3 when the sand percentage is 50% or more as with conventional SFRC.

(2) Fiber content

Figure 6 shows the relationship between fiber content and modified VC value, compaction degree, and air content. The modified VC value increased and compaction degree decreased with an increase in fiber content. These tendencies are particularly clear in the case of indented type I fibers and long fibers, but the difference between fiber types is comparatively small for fiber contents below 1%. In addition, it was observed that type I-1 fiber gathered locally and formed fiber balls and type F fiber remained being combined with water-soluble glue at a fiber content of 1.5%. At this fiber content, therefore, is necessary for the unit water content to be increased to ensure sufficient compaction and fiber dispersion. The air content increased with increasing fiber content with long fibers, but ranged from 1.0% to 2.0% after sufficient compaction.

Figure 7 shows the relationship between fiber content and flexural strength, corresponding to the data shown in Fig. 6. Maximum strength was obtained at a fiber content of 1.0% in the case of long fibers. This is explained by the fact that insufficient dispersion and increased air content at 1.5% cause a reduction in strength, as mentioned above. In the case of short fibers, strength increased as the fiber content increased. However, more compaction was required as indicated in the increase in modified VC value. From these results, the most suitable fiber content was fixed at 1.0%. The unit water content was then determined through trial mixing to achieve a 45 to 55 second modified VC value, with 289 kg/m^3 unit cement content, 40.0% sand percentage and 1.0% fiber content. Figure 8 shows the unit water content and water-cement ratio for each fiber type. The lowest unit water content was without fibers at 107 kg/m^3, and the highest with I-1 was 123 kg/m^3. Water-cement ratios ranged from 37.0% to 42.6% corresponding to this range of unit water content. In the following examination, these mixture proportions were used.

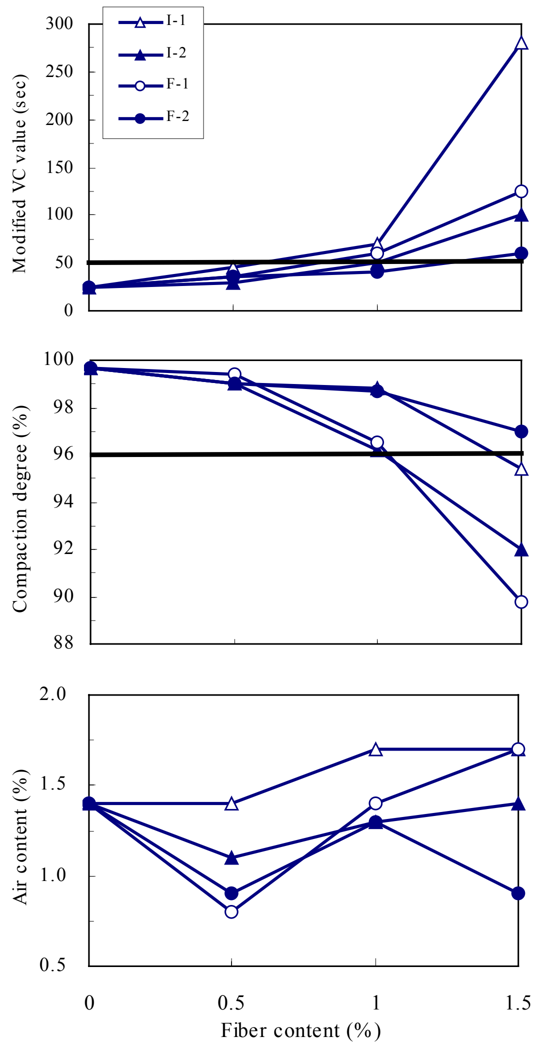

Fig.6 Relationship between fiber content and modified VC value, compaction degree, and air content

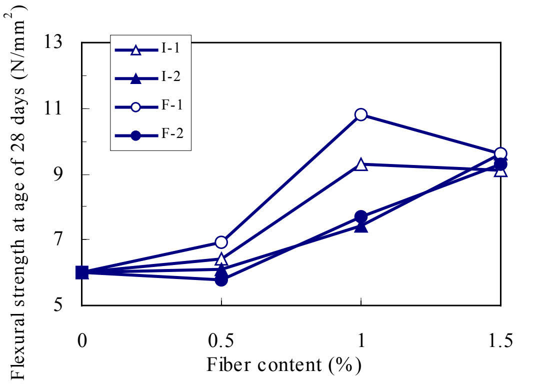

Fig.7 Relationship between fiber content and flexural strength

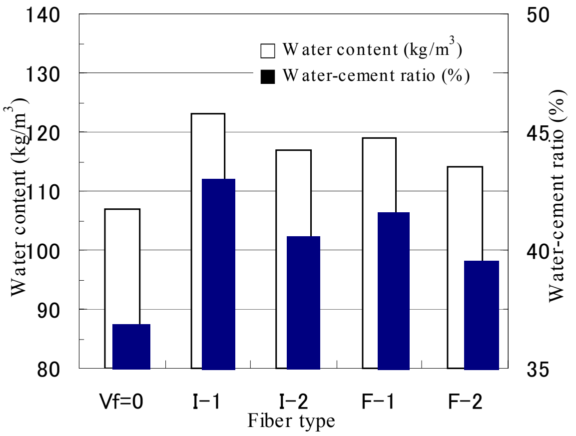

Fig.8 Water content and water-cement ratio of concrete

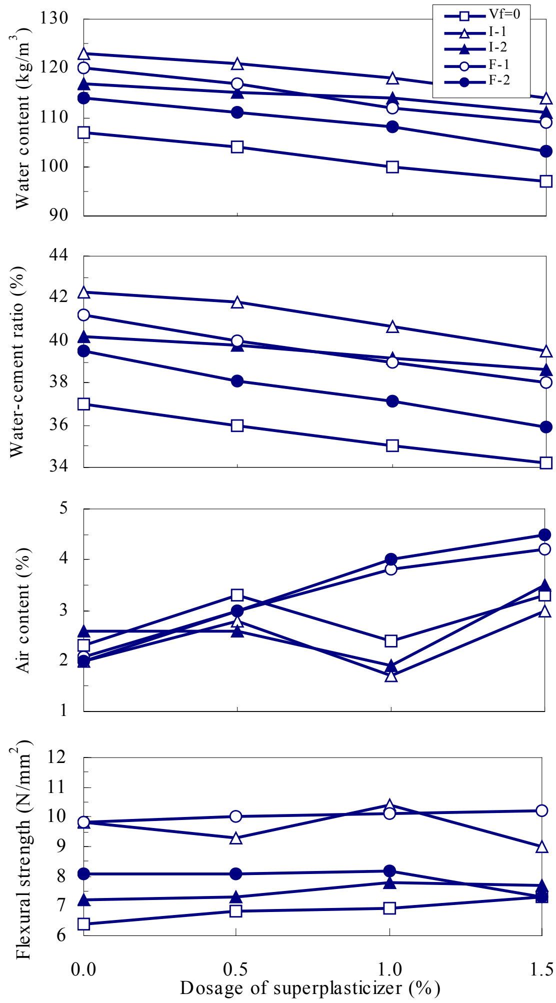

Fig.9 Relationship between dosage of superplasticizer and water content, water-cement ratio, air content, and flexural

(3) Reduction in Unit Water Content by use of Superplasticizer

Figure 9 shows the relationship between dosage of superplasticizer between 0.5% and 1.5%, and unit water content, water-cement ratio, air content and flexural strength. The reduction in unit water content was 3 to 4 kg/m^3 for an increase of 0.5% in dosage of superplasticizer, and unit water content could be reduced by 5 to 10 kg/m^3 at 1.5% dosage compared with the case without a superplasticizer. The corresponding reduction in water-cement ratio was 1.7% to 3.4%. The air content was almost unchanged or slightly higher than without a superplasticizer when the dosage was 1.5%. The flexural strength without fibers increased with an increase in dosage, but with fibers the strength at a dosage of 1.5% was the same or less than at 1.0% dosage.

The reason for this is as follows. The water-cement ratio decreased with increasing dosage, while the unit water content and cement paste content decreased. However, the air voids formed by the aggregate and fibers were not filled by the reduced paste even after full compaction. These remaining air voids would not contribute to strength improvement. These results clearly show that when a superplasticizer is used to reduce the unit water content of SFRCC, an appropriate dosage must be chosen so as to ensure no strength reduction takes place. The appropriate dosage was 1.0% in this study.

4. EXAMINATION OF SEGREGATION AND ORIENTAION OF FIBERS

It has been pointed out that segregation of coarse aggregate and the mortar component should not occur in conventional RCC for pavements[6]. Although an improvement in flexural strength can be expected if steel fiber are added to conventional RCC, which cannot contain reinforcing bars, the degree of segregation compared with conventional RCC must be clarified and it is necessary to investigate differences in fiber orientation due to different compaction procedures such as surface vibration and immersed vibration.

In this chapter, the segregation of coarse aggregate and steel fibers is measured using mix proportions 5 to 9 and 20 in Table 2 and the results are compared with conventional RCC.

The orientation of fibers in SFRCC compacted with a surface vibrator is measured and compared with the results using an immersed vibrator, and the effect of differences in fiber orientation on flexural strength is clarified.

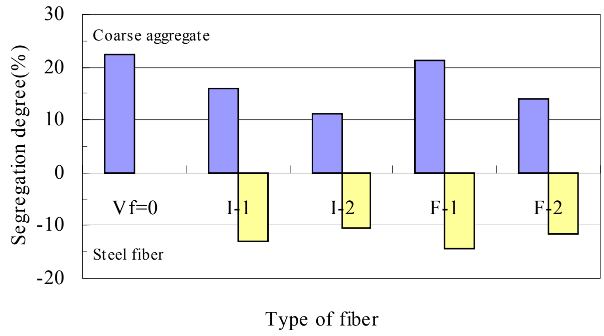

Fig. 10 Segregation of aggregate and steel fibers

(1) Segregation

Figure 10 compares the degree of segregation of aggregate and steel fiber in SFRCC for each fiber type. A decrease of 1.3% to 11.5% in segregation was observed as compared with conventional RCC (V_f=0), and fiber Ⅰ and long fibers were more effective at preventing segregation. These findings are explained as follows. The mortar component of SFRCC, especially when indented fibers are used, is more viscous than that of conventional RCC because of the higher unit water content for a given consistency. The surface texture of indented fibers is less smooth than hooked ones, and this restrains segregation of the coarse aggregate. Long fibers have a lower falling velocity as a result of greater friction on the discharge chute, and they tend to gather near the chute exit; at the same time, coarse aggregate particles dispersed far from the exit. For this reason, long fibers are unable to restrain the segregation of aggregate. However, as use of steel fibers reduces segregation, they are an effective way to provide good quality concrete pavement slabs.

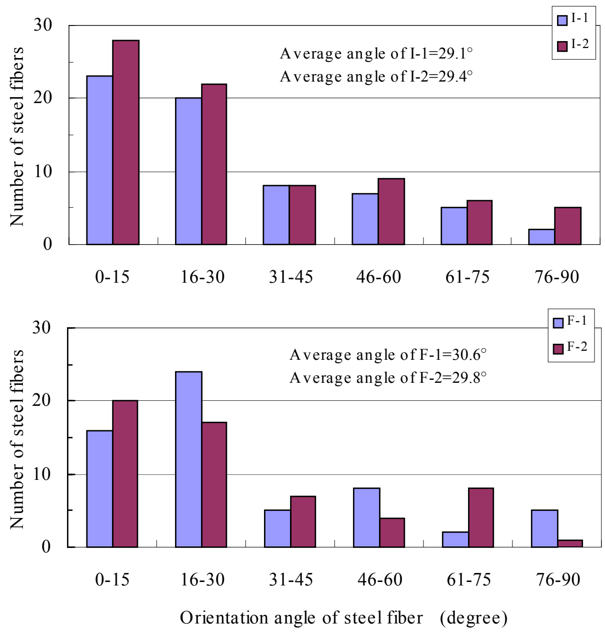

Fig. 11 Distribution of angle to horizontal

(2) Characteristics of Fiber Orientation

Figure 11 shows fiber counts by type at the surface of a specimen for each 15 degrees of angle to the horizontal. About 60 to 90 fibers were counted per specimen, and the average angle to the horizontal is shown in the figure. It can be seen that most fibers are oriented between 0 and 30 degrees, with about 50% of all fibers in this range. Only 2% to 8% of fibers were in the range 76 to 90 degrees. The average angles for I-1, I-2, F-1 and F-2 were 29.1, 29.4, 30.6 and 29.8 degrees, respectively, so there is little variation with fiber type. Figure 12 compares the orientation in the case of short hooked fibers between SFRCC compacted with a surface vibrator and 8cm-slump SFRC compacted using an immersed vibrator. The number of fibers with an angle of 0 to 30 degrees in SFRC is almost the same as in SFRCC, however SFRC contains many fibers in the 30 to 90 degree range, and especially in the 76 to 90 degree range. The average orientation of fibers in SFRCC and SFRC was 30 degrees and 41 degrees, respectively. This difference is due to the different vibration compaction procedure. The surface vibrator used for SFRCC exerts pressure on the concrete layer, and tending to force the fibers into a horizontal orientation, but this is not the case for the

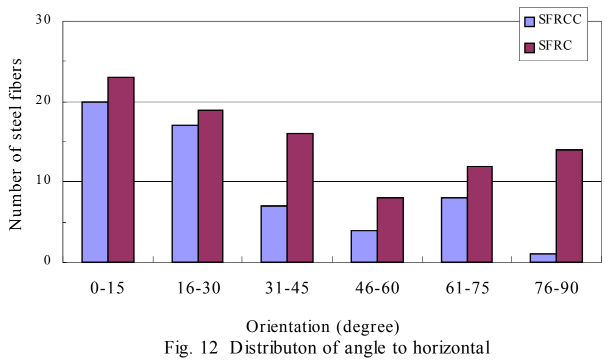

Fig. 12 Distributon of angle to horizontal

immersed vibrator used for SFRC. In case of the immersed vibrator, the mortar component tends to flow under the influence of centrifugal force from the vibrator, and fibers become oriented according to the flow of the mortar component. Figure 13 compares the flexural strength of SFRCC and SFRC with a 40% water-cement ratio. The strength of SFRCC is higher than that of SFRC. The overall horizontal orientation of fibers in SFRCC, as shown in Fig. 12, is thought to effectively reinforce it against the bending moment.

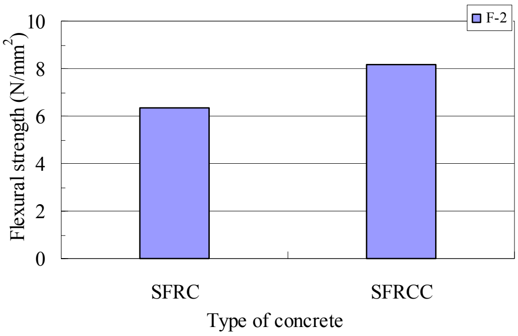

Fig. 13 Flexural strength at 28 days

5. EXAMINATION OF MECHANICAL CHARACTERISTICS

In this section, the flexural strength, flexural toughness and bond strength of SFRCC overlaid on an abraded asphalt pavement surface are examined. Since the need for research on white topping as a repair method for pavement has been pointed out[7)], the bond strength examination was designed to obtain basic data of new method.

Flexural strength was examined for a given mixture or modified VC value (mix proportions 2 and 5 to 9 as shown in Table 2). The load-deflection curve was measured and characteristics of SFRCC deformation for each fiber type were clarified. Furthermore, the bond strength of SFRCC placed on a real used asphalt pavement surface was obtained.

(1) Flexural Strength of Given Mix Proportion and Modified VC Value

Figure 14 shows the consistency of SFRCC measured by the modified VC value for each fiber type. The same mix proportion was used in each case and the VC value was compared with that of conventional RCC $v_{f=0}$. The VC value for SFRCC with indented fibers is higher than that with hooked fibers, and both are naturally higher than that of conventional RCC. This tendency is clearer in the case of long fibers. A lot of cement paste is needed to cover indented and long fibers compared to hooked and short fibers because their surface area is greater, and it is considered that SFRCC using indented and long fibers requires more vibration time to fill the air voids with cement paste. Figure15 shows flexural strengths corresponding to Fig.14, in which the compaction degree of the SFRCC specimen was 98.5% to 99.8%. The strength of SFRCC is 26.3% to 82.1% higher than that of RCC depending on the type of fiber. This difference can be attributed to the reinforcement effect of the fibers because the same mix proportion is used. The effect is

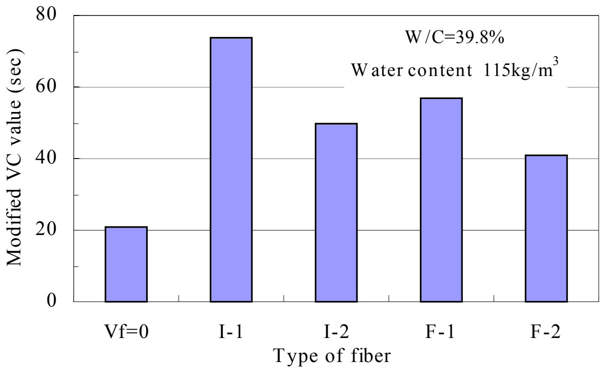

Fig. 14 Comparison of modified VC value

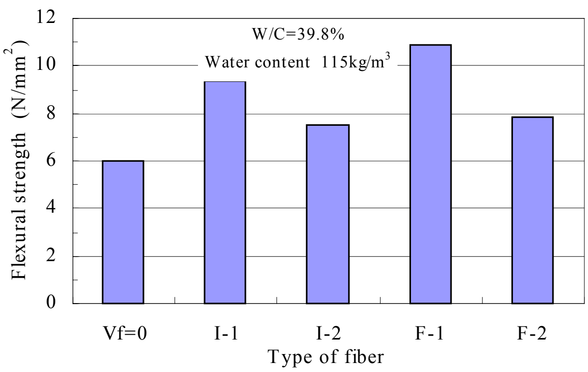

Fig. 15 Comparison of flexural strength

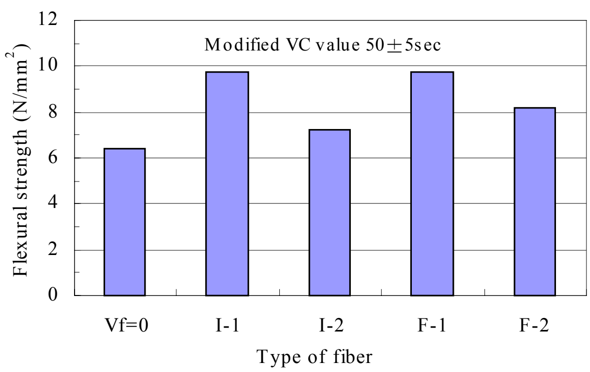

Fig. 16 Comparison of flexural strength

particularly evident in the case of the long hooked fibers. Figure16 shows the flexural strength of SFRCC and conventional RCC for a given modified VC value. The differences in strength are similar to those in Fig.15, and the strength of SFRCC is 12.5% to 52.3% higher than RCC. It is considered that the slightly reduced reinforcement effect in this case results from the increase in water-cement ratio required to maintain the same consistency. Despite this, the reinforcement effect still remains 10% more than conventional RCC. In addition, the relative error of strength tested the same concrete, defined as the difference between the maximum and minimum values divided by the average, is 7.9% for RCC and 1.1% to 8.8% for SFRCC. The relative error of SFRCC with type I fibers was lower than that of SFRCC with type F fibers and RCC. It seems that this is related to the low degree of segregation of SFRCC containing type I fibers, as shown in Fig. 10.

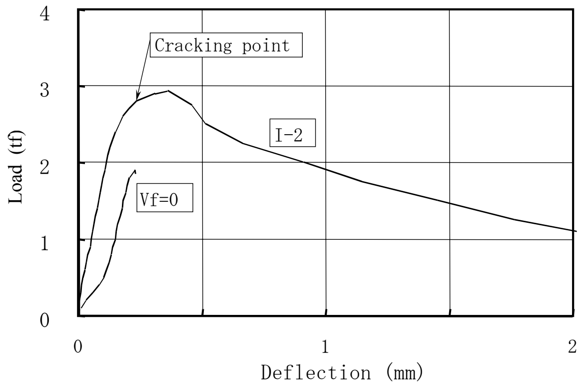

Fig. 17 Load - Deflection curve of SFRCC and RCC

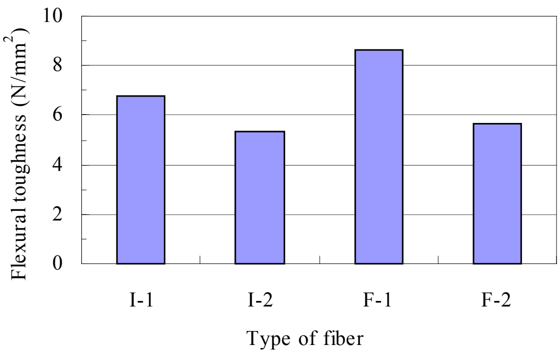

Fig.18 Comparision of flexural toughness with different fiber types

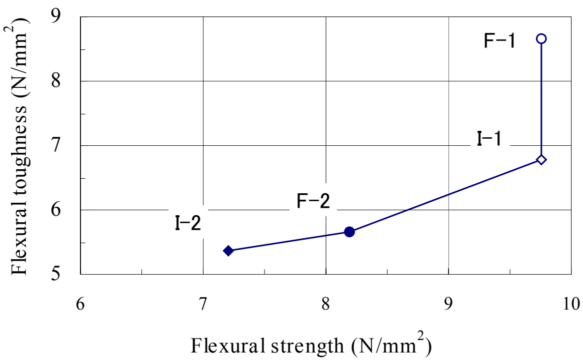

Fig.19 Relationship between flexural strength and toughness

(2) Load-deflection Curve and Flexural Toughness

Figure 17 shows examples of load-deflection curves for SFRCC and conventional RCC beam specimens. In the case of conventional RCC, deflection increases linearly with rising load before dropping at the maximum load. On the other hand, the deflection of SFRCC increases linearly but at a lower rate. Cracking occurs at a certain load that is higher than in the case of RCC. The curve turns at this point, but the beam continues to support the load until the maximum load. After the maximum load, the deflection increases considerably and the beam can still support the load. It is thought that the bearing capacity of SFRCC is related to the fiber pulling-out process. Figure18 shows the toughness of SFRCC for each fiber type. The toughness of SFRCC with hooked fibers is 0.31 to 1.88 N/mm2 higher than in the case of indented fibers, while the toughness of SFRCC with long fibers is 1.42 to 2.99 N/mm2 higher than in the case of short fibers. Figure19 shows the relationship between flexural strength and toughness for SFRCC with different fibers. The toughness increases with increasing strength, so toughness is affected by fiber length and shape. This result is the same as with conventional SFRC[8)]. The better mechanical properties of SFRCC using hooked fibers result from a difference in anchorage effect, which depends on fiber type. In addition, the relative error of SFRCC flexural toughness was 5.6% to 16.7%, and the relative error of type F fibers was smaller than that of type I fibers.

(3) Bond Strength with Asphalt Pavement

Figure 20 shows the bond strength for each fiber. The bond strength between the asphalt surface and the two types of concrete, SFRCC and conventional RCC, at the age of 1, 3 and 7 days was 0.43 to 0.50, 0.57 to 0.71, and 0.72

to 0.90 N/mm^2, respectively. The difference between maximum and minimum bond strength was 0.07, 0.14 and 0.18N/mm^2 at the age of 1, 3 and 7 days. No difference in bond strength depending on fiber shape and size can be seen. In a past investigation[9)], the bond strength between SFRC and asphalt pavement was 0.4 N/mm^2 and, at the age of 7 days, was independent of the presence of steel fibers. It is therefore concluded that the bond strength of SFRCC to an asphalt pavement is not affected by the presence of steel fibers. Some asphalt mortar is observed on the concrete surface after bond strength testing, so the bonds in the asphalt mixture are destroyed. Some difference in bond strength among specimens was observed for the some age and type of fiber. It is thought that the bond strength with the asphalt pavement surface depends on the roughness of the abraded asphalt pavement, which directly affects the bond area.

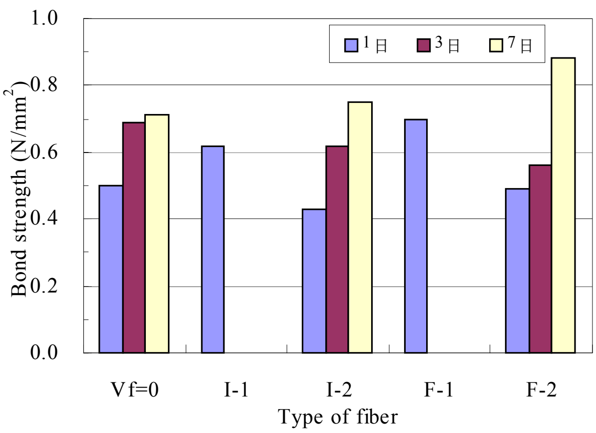

Fig.20 Bond strength between concrete and asphalt pavemnet

Figure 21 shows the development of bond strength in SFRCC and conventional RCC with age. Bond strength increased with age regardless of the presence or type of fibers. In this study, the bond strength of SFRCC at 7 days was 0.7 to 0.9 N/mm^2, much higher than in past investigations.

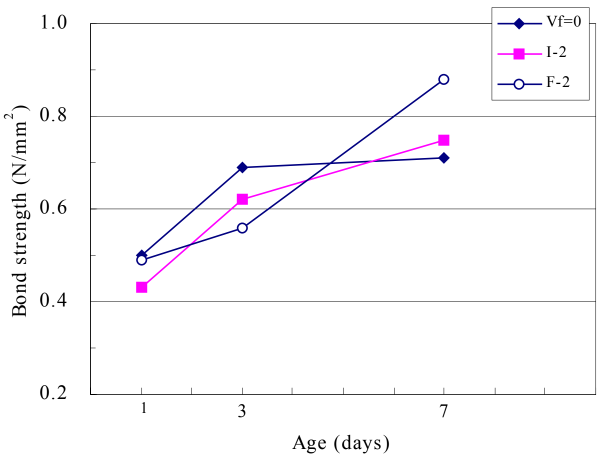

Fig.21 Change in bond strength with age

The reason for this result seems to be use of direct pull-out tensile strength method an SFRC and smooth asphalt plates prepared in the laboratory in the earlier investigations whereas in this study the splitting tensile strength method and asphalt blocks obtained from an actual traffic route were used. The bond strength between SFRCC and an asphalt pavement can be expected to reach 0.7 N/mm^2. Further, the relative error of bond strength at 3 days was 26.2% for conventional RCC and 23.7% to 38.5% for SFRCC.

6. EXAMINATIONS OF FREEZING-THAWING RESISTANCE AND DRYING SHRINKAGE

One of the known characteristics of conventional RCC is that freezing-thawing resistance can be secured by sufficient compaction and air entrainment while the drying shrinkage of RCC is lower than that of normal concrete. On the other hand, it is well known that the freezing-thawing resistance and drying shrinkage of SFRC are superior to those of normal concrete.

In this section, the freezing-thawing resistance and drying shrinkage of SFRCC are examined. Freezing-thawing resistance was examined using mix proportions with and without an AE agent (mixes 5 to 9 and 15 to 19) while drying shrinkage was investigated with and without fibers (mixes 5 to 9) to clarify the effect of using fibers.

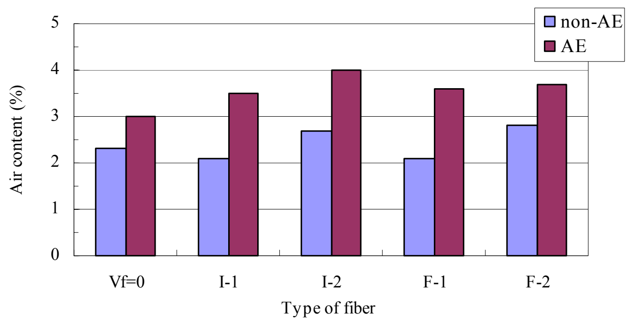

Fig. 22 Comparison of air content with different fiber types

(1) Freezing-thawing Resistance

Figure 22 shows the air content of each type of SFRCC and of non-fiber RCC. These air contents were measured by a gravimetric method. According to Fig.22, the air content of SFRCC and conventional RCC with an AE agent is 0.7% to 1.5%, more than when no AE agent is used. The unit water content when the mix contains an AE agent is 2 to 5 kg/m^3 less than when no AE agent is used, as shown in Table 2. Figure 23 shows the freezing-thawing test results for SFRCC and conventional RCC. The relative dynamic modulus of elasticity of SFRCC with an AE agent after 300 cycles is 68.2% to 83.0%, while that of conventional RCC is 61.0%. In the case of non-AE concrete, the modulus falls below 60% at the 74th to 170th cycle for SFRCC and at the 74th for conventional RCC, respectively. The freezing-thawing resistance of concrete is therefore improved by including the steel fiber and adding the AE agent. The middle and bottom figures in Fig.23 show the ultrasonic pulse velocity of SFRCC and the weight loss of SFRCC and conventional RCC. The ultrasonic velocity of SFRCC is higher than that of the RCC, and when an AE agent is included it is higher still. This reflects the results for relative dynamic modulus. The weight losses of SFRCC and RCC with an AE agent are more than when no AE agent is used. Of particular note is the result that the weight loss values of RCC and SFRCC I-1 without an AE agent are negative. This means the concrete absorbs water as it deteriorates under testing. This phenomenon also seems to occur locally in other types of SFRCC without an AE agent. It has been pointed out that the frost resistance of RCC is dramatically reduced if compaction is insufficient[10), 11)]. The degree of compaction of the test specimens used in this study was 98% to 99% and the effect of this variation on frost resistance was negligible. Surface mortar was observed to peel off in the case of non-AE concrete, but not in the case of SFRCC with an AE agent. Figure 24 shows the relationship between flexural strength ratio and durability factor when an AE agent is used. The strength ratio represents the ratio of strength after and before the freezing-thawing test. Strength ratio increases with increasing durability factor and for SFRCC both values are plotted in the upper right-hand corner of this figure. These various results allow us to conclude that the steel fibers restrain cracking under frost action and improve the frost resistance of SFRCC.

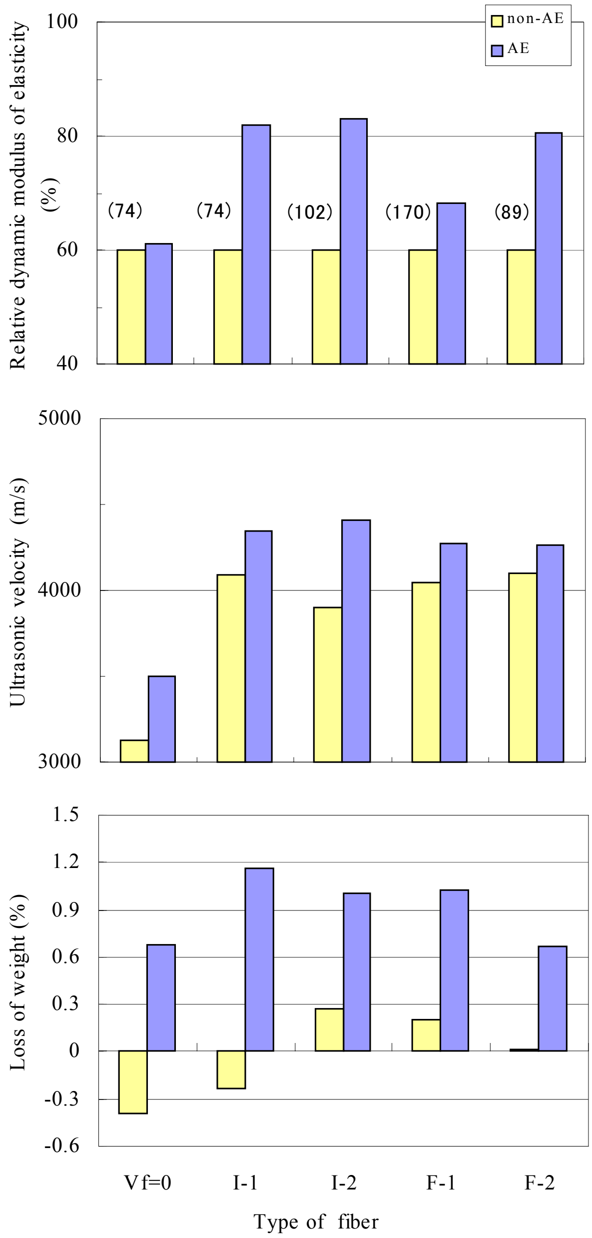

Fig. 23 Freezing-thawing resistance of SFRCC and RCC

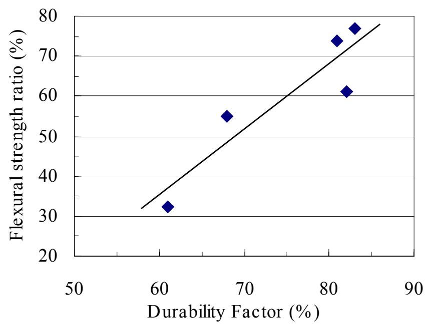

Fig.24 Relationship between durability factor and flexural strength ratio

(2) Drying Shrinkage Characteristics

Figure 25 shows the drying shrinkage strain, length change ratio, and loss of weight of SFRCC for each fiber type and of conventional RCC at 190 days during the drying tests. The drying shrinkage strain is 5.4×10^{-4}

for RCC, and 5.0×10^{-4} to 5.7×10^{-4} for SFRCC, respectively. The length change ratio of SFRCC as compared with RCC is 91.7% to 104.2%. The loss of weight is 1.65% for RCC and 1.61% to 1.88% for SFRCC, respectively. Thus the drying shrinkage strain of SFRCC is almost the same as that of RCC. The weight loss of SFRCC is no less than that of RCC. It is well known that the higher the unit water content, the more significant the drying shrinkage. In this study, the unit water content of SFRCC was 7 to 16 kg/m^3 more than that of the RCC, as required to maintain a constant modified VC value. So the weight loss of SFRCC is more than that of RCC, but the drying shrinkage is almost the same. It is therefore concluded that steel fibers are able to restrict drying shrinkage strain in a dry environment.

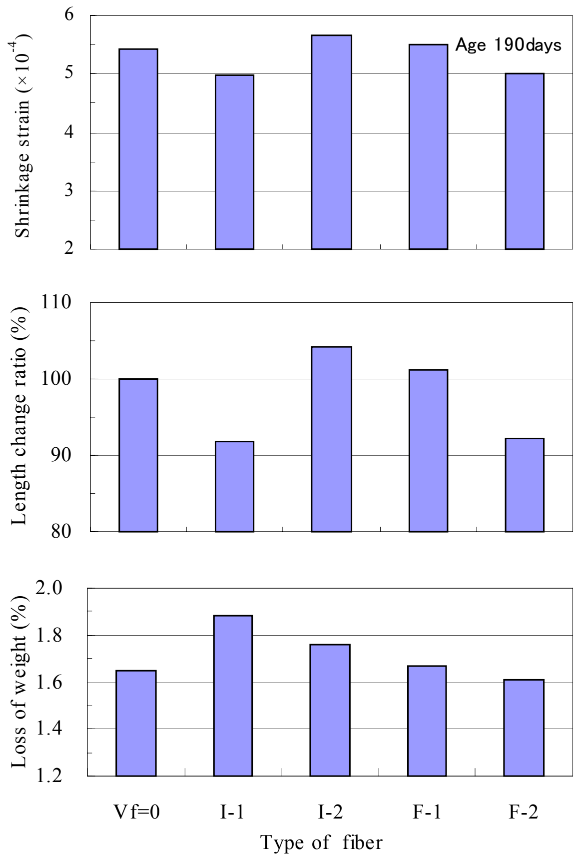

Fig. 25 Comparison of shrinkage properties of SFRCC and RCC

7. CONCLUSIONS

This study clarifies that the mix design procedure for SFRCC to be used as pavement material is the same as for conventional pavement concrete in that the choice of appropriate sand percentage and fiber content is very important. The properties of hardened SFRCC, such as flexural strength, are remarkably better than those of conventional RCC. The conclusions reached with respect to mix proportion and the properties of fresh and hardened SFRCC are given below.

(1) The modified VC value of SFRCC is greater than that of conventional RCC, and the change in VC value for each 1 kg/m^3 change in water content is about 3 to 4 seconds, regardless of the presence of fibers. For a given unit water content, there exists a sand percentage at which the modified VC value reaches a minimum and the compaction degree a maximum. This sand percentage is about 40% regardless of fiber type and the modified VC value with type I fibers or long fibers at the minimum sand percentage is higher.

(2) Regardless of fiber type, a 1.0% fiber content appears to be the optimum, taking into account the unit water content, compaction degree, dispersion of fibers and flexural strength. The unit water content of conventional RCC at a modified VC value of 50 seconds is 107 kg/m^3 and that of SFRCC is 123 kg/m^3 and 117kg/m^3 for short and long type I fibers, and 119 kg/m^3 and 114 kg/m^3 for short and long type F fibers.

(3) The unit water content can be reduced by 3 to 4 kg/m^3 per 0.5% increase in the dosage of a superplasticizer, but in some cases, a reduction in flexural strength is seen due to the formation of voids if the dosage exceeds 1.5%. Thus a 1.0% dosage of superplasticizer is the optimum as determined in this study.

(4) The segregation of coarse aggregate in SFRCC is less than in conventional RCC. SFRCC with indented fibers or short fibers has better segregation resistance.

(5) The average orientation of fibers in SFRCC is 29.1 to 30.6 degrees irrespective of fiber type, about 10 degrees less than in conventional steel fiber reinforced SFRC compacted by immersed vibrator. As a result, the flexural strength of SFRCC is about 30% higher than that of SFRC.

(6) The flexural strength of SFRCC for a given consistency is 12.5% to 52.3% higher than that of conventional RCC. The flexural toughness of SFRC with hooked fibers is 0.31 to 1.88 N/mm^2 higher than with indented fibers. The toughness of SFRC with long fibers is 1.42 to 2.99 N/mm^2 higher than with short fibers.

(7) The bond strength of SFRCC when applied as a white topping to an asphalt pavement surface is 0.7 N/mm^2 at 7 days, regardless of fiber type and size.

(8) The freezing-thawing resistance of SFRCC with an AE agent is much better than that of conventional RCC. The relative dynamic modulus of elasticity of SFRCC after 300 cycles of testing is 68.2% to 83.0%.

(9) In spite of the higher unit water content of SFRCC for a given consistency, the drying shrinkage strain of the concrete is almost the same as that of conventional RCC after 190 days of drying.

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