

**STUDY ON SHRINKAGE CRACK IN REINFORCED
CONCRETE DECK SLABS OF HIGHWAY BRIDGES**

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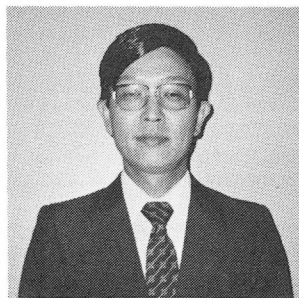
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SYNOPSIS

One of the more serious problems in the maintenance and repair in steel highway bridges is that of the deterioration of reinforced concrete deck slabs through cracking. In this study it was shown clearly by three years of field investigation of the slabs before service that the mechanism of crack occurrence was closely related to the shrinkage of concrete. An analytical method to predict shrinkage cracking was developed, and some improvements of materials and mix proportioning of concrete to prevent shrinkage cracks were examined.

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1. INTRODUCTION

There are many reports available on the deterioration of the reinforced concrete deck slabs of steel highway bridges in Japan[1]. This deterioration has become a social problem especially in urban viaducts adjacent to public service facilities such as parks or streets because it may be directly connected with an accident if a part of the concrete cover of the reinforced concrete slab peels off and falls. There are many structures currently needing immediate maintenance and repair.

In the reinforced concrete slabs of highway bridges, the ratio of the live load to the total load is much greater than that in other reinforced concrete structures, and wheel loads act directly on it. The amount and numbers of wheel loads sometimes exceed the design values; therefore the deterioration of slabs may be caused by fatigue due to the increased traffic volume containing heavy loads. And this fact led to several revisions and changes in design codes in the last two decades (see Table 1)[5].

Former investigations of this problem were mainly based on the evaluation of the relationship between the load bearing capacity of the slab and the external forces. However, there are many other factors affecting the deterioration of slabs. There are for example, the utilization of poor quality aggregates due to shortages of quality materials and the use of concrete mixes containing large amounts of mortar for pumping, etc. It follows that drying shrinkage and the resultant restrained tensile stress in concrete increase resulting in many shrinkage cracks. These cracks will decrease the rigidity of slab as well as the effective width of compressive flanges of deck beams, and will adversely affect the durability and the fatigue properties of these reinforced concrete slabs. Many studies on shrinkage properties of concrete have been conducted, but almost all the studies are concerned with laboratory shrinkage tests and there are few which are based on the in-situ data. It is generally difficult to correlate laboratory data to those of the in-situ concrete investigations because drying shrinkage is affected by the shape and dimension of members, environmental conditions such as temperature, humidity, rainfall and wind, and the materials used and concreting conditions. In this study, focussing on a premature deterioration due to shrinkage cracks, field investigations of shrinkage cracks on deck slabs before service and laboratory shrinkage tests of concrete to evaluate the effects of materials and size of specimens were carried out. An analytical method to predict shrinkage cracks was also developed, and

Table 1 History of revisions of code requirements for highway bridge deck slab

code revised or recommended at	name of code	requirements					
		wheel load P (kg)	bending moment(kg.m)		allowable stress of steel bar (kg/cm ²)	amount of lateral reinforcement	minimum thickness of slab (cm)
			longitudinal	lateral			
1956	Spec.of JRA**	8000	2m< L <4m L:span $\frac{0.4P(L-1)}{L+0.4}$	not specified	1200	not specified	11*
1964	Spec.of JRA				1800 for SSD49 & SD30	more than 25% of long. steel	14
1967	tentative recommendation				1400 for SD30	more than 70% of long. steel	
1968	tentative recommendation						
1971	tentative recommendation	8000, or 9600 when traffic volume is more than 1000 heavy vehicles per day	0.8(0.12L +0.07)P	0.8(0.10L +0.04)P			3L+11>16
1973	Spec.of JRA						
1978	tentative recommendation						1400 but margin of about 200 is recommended

note *:effective depth, **:Specifications for Highway Bridge (Japan Road Association)

some improvements in materials and mixes of concrete to prevent the initial defect were examined.

2. FIELD INVESTIGATION OF CRACKS ON DECK SLAB

In ordinary reinforced concrete structures occurrence of tensile or shrinkage cracks is not a serious problem, but when several unfavorable conditions coincide, for example in the environment, the materials and in the structural and concreting conditions, shrinkage cracks may become a serious problem. Deck slabs are one structure which may be subjected to the above unfavorable conditions. In this study, first, about three years of pre-service observations of the bottom surfaces of the concrete deck slabs were carried out on two steel girder bridges. One of these is shown in Fig.1. In addition to these observations, crack width and ultrasonic velocity measurements and Schmidt-hammer tests were also done. As an example of the test results, cumulative distribution curves of crack density are shown in Fig.2. The following results were obtained from the investigation:

(1) Shrinkage cracks grow continuously until about three years after construction. In Fig.2 the cumulative distributions of crack density at four measuring ages of 60, 400, 760 and 1120 days are given.

(2) Rsch's equations for predicting the development of shrinkage of concrete are often used in design, for example, in DIN1045 and in some codes in Japan. The coefficient k_s of the equation is shown in Fig.3 as a function of effective age. The increase of crack density with time observed in the bridges and expressed in Fig.2 can be approximated by the Rsch's equation in which the effective depth d_v is taken as 20cm. In Fig.3 the ratio of k_s to its final value $k_{s, \text{final}}$, which means the progress of shrinkage strain with time, becomes 30, 54, 73 and 86% for the ages of 50, 200, 500 and 1000 days respectively, and the progress of crack density on the actual deck slab shows almost the same tendency.

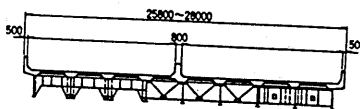


Fig.1 Continuous steel girder bridge of the field investigation

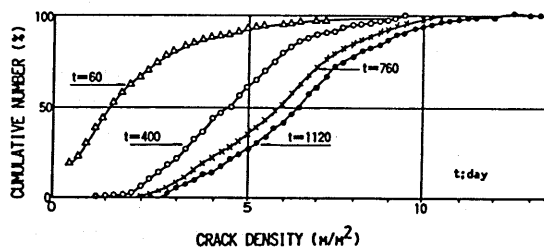
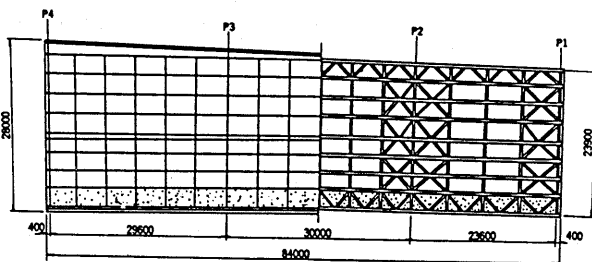


Fig.2 Cumulative distributions of crack density

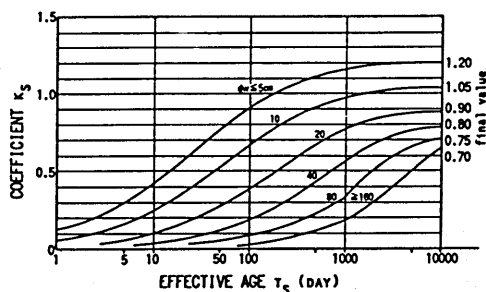


Fig.3 Relationships between k_s and t_s

(3) Crack patterns were clearly affected by constraint due to the main steel girders, and showed lateral cracks perpendicular to the axis of the bridge in the region between the supports; however near the end of the bridge, diagonal cracks at an angle of 45 deg. were observed because of additional constraint due to the end cross beam.

In some part of the slab, large shrinkage cracks having greater width than 0.2mm were observed, and there were a few cases where repairs were necessary.

3. ANALYSIS OF SHRINKAGE STRESS

3.1 Shrinkage and Creep of Concrete

It is important to predict analytically this type of crack occurrence due to shrinkage in order to prevent the deterioration of deck slabs. Shrinkage and creep properties of concrete are affected by many factors such as composition, mix proportion, size of members and environmental conditions, and it is difficult to take all of the above factors into account in the analysis. In this study, therefore, an analytical method based on the some assumptions as mentioned below was tried and the result of the analysis was compared with the observed cracks on the actual deck slab. A laboratory test of model girders was also carried out in order to examine and to verify the analytical method. The assumptions are as follows:

(1) Rüsch's equations for development of shrinkage and creep of concrete can be used in the analysis.

(2) The effects of materials, mix proportion and drying condition are assumed to be able to be considered by using appropriate values for the basic shrinkage strain and the base value of flow in creep.

(3) The effect of the sizes and shapes of members is also estimated by using Rüsch's equations.

Many experimental equations have been proposed on the development of shrinkage and creep of concrete under certain conditions. In some investigations the size effect was analyzed on the assumption that the mechanism of shrinkage could be approximated by a linear or non-linear diffusion equation[4]. Such analyses may be quite effective in studying the internal stress in a thick cross section due to self-confinement of shrinkage. The slab analyzed here is, however, comparatively thin and self confining stress is considered to be insignificant. So a uniform shrinkage strain distribution was assumed in this analysis.

3.2 Step-by-Step Analysis of Shrinkage Stress

Shrinkage stress in a simple structure can be analyzed by a method such as Dischinger's method[6,7] in which similar types of development of shrinkage and creep are assumed. But this method is not applicable in cases of different types of development of shrinkage from creep and delayed elastic strain. In those cases a step-by-step procedure is

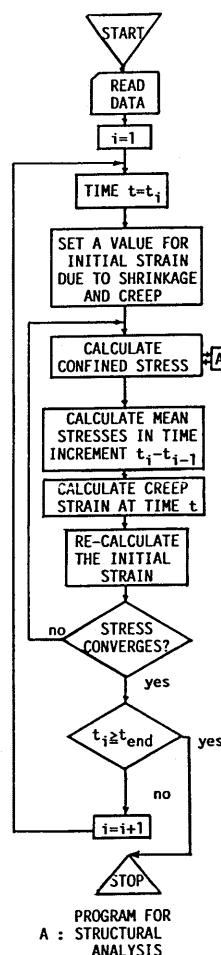


Fig.4 Flow of the analysis

applicable, and though it is an approximate method, its result is accurate when adequate time intervals are used. The flow of this analysis is shown in Fig.4.

3.3 Structural Analysis

The steel girder bridge which was chosen for this analysis was designed as a non-composite girder, but it generally behaves as a composite girder. Therefore, in this analysis the concrete slab is assumed to be composited with the steel girder. Concrete strain in the slab is restrained longitudinally by both a main girder and longitudinal reinforcing bars. In a statically indeterminate structure such as a continuous beam, additional restrained stress is introduced by the reactions due to shrinkage. On the other hand, lateral constraint is mainly due to lateral reinforcements in the slab and to a cross beam near its support. Generally the lateral constraint is much less than longitudinal, and in this analysis the effect of the lateral constraint is neglected.

A simply supported composite girder with a span of 40m, and a continuous composite girder with three spans as shown in Fig.1 were chosen as the subjects of this analysis. The length of each span of the continuous girder was assumed to be approximately 30m. An analysis of a model girder as described in section 4 was also carried out. All the girders have I-shaped sections. The following were assumed in the structural analysis:

- (1) The girder is divided longitudinally into a certain number of segments as shown in Fig.5.
- (2) The cross section is divided into three parts; the steel girder, the concrete of the slab and the reinforcing bars in the slab.
- (3) The adjacent steel girder segments are connected with each other only at nodal points located on the upper surface of the steel girder at the end of the segments.
- (4) The adjacent concrete segments are connected with each other only at nodal points located under the bottom surface of the slab at the end of the segments.
- (5) The reinforcing bars in the slab are connected at both ends of the concrete segment.

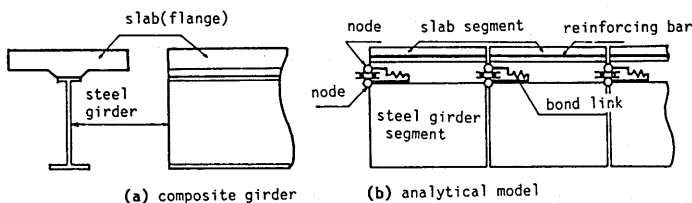
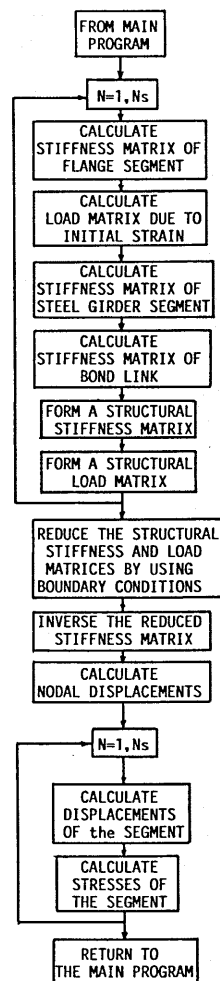


Fig.5 Analytical model of the composite girder



Ns : number of segments

Fig.6 Flow of structural analysis

- (6) Vertical relative displacements between the slab and the steel girder are neglected, and horizontal relative displacements are restrained at the nodal points by bond links (see Fig.5).
- (7) All the materials and the bond links are linear elastic. The beam theory is applicable to the concrete and steel girder segments, and the reinforcing bar resists only longitudinal forces.

The matrix stiffness method was used in the analysis, the flow of which is shown in Fig.6. Coefficients for creep and shrinkage and moduli of elasticity used in the analysis are listed in Table 2.

Table 2 Conditions of the numerical analysis

basic shrinkage strain ($\times 10^{-5}$)	final value of delayed elasticity	base value of flow	elastic modulus of concrete
20 40 60 80	0.4	1.0 2.0 3.0	$3.0 \times 10^5 \text{ kg/cm}^2$ ($2.94 \times 10^4 \text{ MPa}$) constant

note: shrinkage was assumed to start at the age of 7 days.

3.4 Analytical Results

The restrained tensile stress occurring on the bottom surface of the slab in the mid span of the simply supported girder is listed in Table 3. The restrained stress, of course, increases in proportion to the basic shrinkage strain, while it decreases with the increasing base value of flow because of remarkable stress relief due to creep. This tendency becomes significant as the time progresses, and the stress reduction varies 7-8% at the age of 100 days and 9-11% at 1000 days each corresponding to the increase of the base value of flow by 1.0. The longitudinal reinforcing bars have a great effect on the restrained stress, for instance, 40% greater stress than that obtained without reinforcing bars.

Fig.7 shows the relationship between time and the restrained stress occurring on the upper surface of the concrete slab in the middle of the center span of the three span continuous girder. The longitudinal restrained stress distribution at the age of 100 days is shown in Fig.8 when the basic shrinkage strain is 80×10^{-5} . The restrained stress due to a temperature difference of 10 deg. C. between the slab and the girder is also shown in Fig.8, where the coefficient of linear expansion of concrete and steel of $1.0 \times 10^{-5}/^\circ\text{C}$ is used in the analysis. Fig.9 shows the deflection curves at the ages of 100 and 1000 days.

In the field investigation, visible cracks were first observed at the age of about three months, and the calculated restrained tensile stresses at the age of 100 days are 10 kg/cm^2 (0.98MPa) for the simply supported girder (see Table 3) and 20 kg/cm^2 (1.96MPa) for the continuous girder (see Fig.7) both corresponding

Table 3 Analytical results of restrained stress(the simply supported girder)

basic shrinkage strain ($\times 10^{-5}$)	base value of flow	reinforcing bars in the slab not considered			reinforcing bars in the slab considered		
		100days	1000days	max.value	100days	1000days	max.value
20	1.0	2.0	4.4	5.1	2.8	6.3	7.2
40		4.0	8.9	10.2	5.6	12.5	14.3
60		6.0	13.3	15.2	8.4	18.8	21.5
80		8.0	17.8	20.3	11.2	25.0	28.6
80	2.0	7.4	16.0	17.5	10.5	22.6	25.2
80	3.0	6.9	14.7	16.0	9.9	20.8	22.7

unit: kg/cm^2 ($\times 98 \text{ MPa}$)

to the basic shrinkage strain of 80×10^{-5} . This is because the deflection due to shrinkage is restrained by the intermediate supports in the continuous girder and additional stresses are induced by the statically indeterminate moment. The longitudinal stress distribution in Fig.8 is trapezoidal, showing a nearly constant and maximum stress in the center span and inclined stress distributions in the side spans. In the center span of the continuous girder the restrained stress induced by the temperature change of 10 deg. C is about 10 kg/cm^2 (0.98MPa), and when it is added to the shrinkage stress, a total restrained stress becomes about 30 kg/cm^2 (2.94MPa) and the probability of occurrence of cracks is high.

It is necessary to examine whether the basic shrinkage strain and the base value of flow in creep used in this analysis represent the typical values of the concrete used in Japan. In the following section, shrinkage properties of concrete were investigated, and a model girder test was carried out.

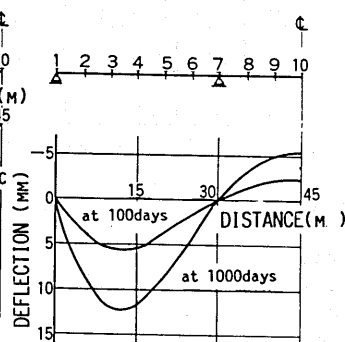
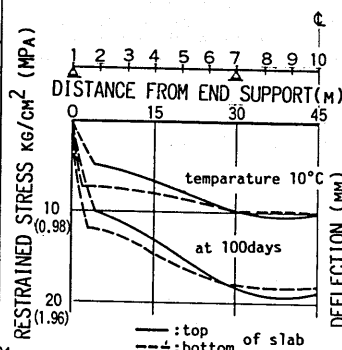
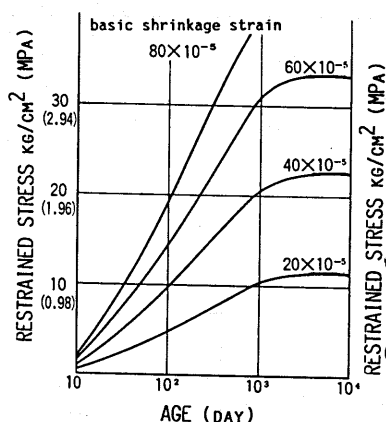


Fig.7 Restrained stress

Fig.8 Restrained stress distribution
(basic shrinkage strain : 80×10^{-5})

Fig.9 Deflection curves
(basic shrinkage strain : 80×10^{-5})

4. SHRINKAGE TESTS OF CONCRETE

4.1 Test to Examine the Effect of Size of Specimen and of Types of Aggregates

(1) Outline of the Test

Many laboratory tests on shrinkage properties of concrete have been carried out in Japan, and many of them are based on the JIS A1129-1975 (Methods of Test for Length Change of Mortar and Concrete). In the JIS test, test specimens of $10 \times 10 \times 40$ (or 50) cm are used, and it is useful to compare the test results with each other. The observed shrinkage strain of the recent mix of concrete by the JIS test is about 100×10^{-5} at the age of 3 months under the condition of R.H.60%. However, a value of $15-20 \times 10^{-5}$ is used for shrinkage in design, taking into account the practical effects of reinforcing bars and of creep of concrete. These effects, however, should be considered separately in detail when the premature deterioration of reinforced concrete slabs due to shrinkage as described in section 3 is estimated.

In order to correlate the JIS test results with the actual structural concrete, the effect of size on the specimen was examined for several concrete mixes. Table 4 shows the mix proportions of concrete specifically designed for use in

Table 4 Mix proportions of concrete

mix	coarse aggregate kind	max. size	slump (cm)	air (%)	W/C	S/a (%)	unit content (kg/m ³ (x98kN/m ³))						
							water W	cement C	fine aggregate S			coarse aggregate	admixture WRA**
									sea sand	crushed sand	BFS* sand		
A	crushed	20	15.0	6.0	50	41	170	340	714	---	---	1078	Cx0.0025
B	crushed	20	12.6	8.2	50	39	178	356	333	343	---	1094	Cx0.0025
C	crushed	20	13.9	6.9	50	42	168	336	243	250	264	1064	Cx0.0025
D	crushed	20	6.7	5.0	50	41	170	340	714	---	---	1078	Cx0.0025
E	crushed	40	10.7	4.0	50	35	162	324	620	---	---	1217	Cx0.0025
F	light weight	15	16.0	6.8	50	41	168	336	714	---	---	567	Cx0.0025

* : BFS sand: granulated blast furnace slag fine aggregate which was made by being chilled by air

** : WRA : air entraining water reducing agent

note: Tabulated values of slump and air are measured values, and the above concretes were mixed on the basis of the specified mixes in which target values of slump and air were 10±2 cm and 5±1% respectively.

Table 5 Test specimens

No.	V/S (cm)	size of specimen (cm)	surfaces exposed to drying	item	series I			series II		
					A	B	C	D	E	F
No.1	2.2	10x10x40	6	JIS specimen	*	*	*	*	*	*
No.2	2.2	10x10x40	6	This specimen was made of the mortar in the above concrete	*	*	*	---	---	---
No.3	5.0	10x10x40	2	to investigate the effect of V/S ratio	*	*	*	*	*	*
No.4	7.5	15x10x40	2	the minimum thickness specified in 1964	*	*	*	*	*	*
No.5	10.0	20x10x50	2	The thickness after 1971 is associated	*	*	*	*	*	*
No.6	12.5	25x10x50	2	The thickness after 1980 is associated	*	*	*	*	*	*

note: *: shrinkage test, **: shrinkage and creep test

bridge deck slabs and produced in the Kansai area (Western Japan). The test program is divided into two series. **Series I** consisted of mixes A, B and C respectively containing sea sand, mixed sand of sea and crushed sand, and BFS sand (granulated blast furnace slag sand) for fine aggregate. **Series II** consisted of mixes D, E and F each with the same fine aggregate plus crushed gravel of maximum sizes of 20mm or 40mm, or light weight aggregate (Lionite) was used for coarse aggregate respectively. The sizes of test specimens are listed in Table 5, and the ratio of the volume to the surface subjected to drying, V/S for each specimen is also listed in the table. The effective thickness d_w in Fig.3 is equal to two times V/S ratio. The details of the specimens are shown in Fig.10, and side surfaces of all the specimens except No.1 and No.2 were sealed with water proof sheets to prevent drying. The specimens were demoulded one day after casting, and then cured in the water at a temperature of 20°C for 7 days. Then the specimens of series I and II were dried in the rooms of relative humidity of 60 and 70% respectively, at a constant temperature of 20°C. Contact strain gauges were used to measure the length change of the specimens, and the weight change of the specimens was measured by a balance having a capacity of 30kg and sensitive to 2g.

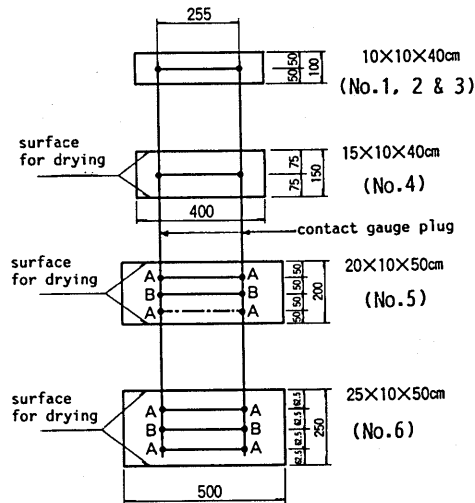


Fig.10 Details of the specimens

(2) Test Results and Discussions

The relationships between shrinkage strain and the V/S ratio for concrete in series II are shown in Fig.11. The effect of the quality of the fine aggregate on shrinkage is noticeable and the final values of shrinkage are 87, 112 and

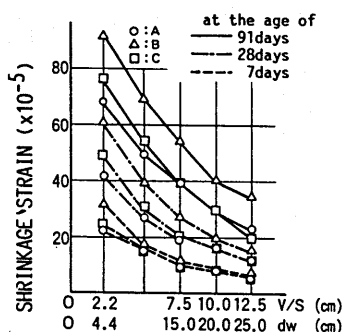


Fig.11 Relationships between shrinkage strain and V/S

97×10^{-5} for the JIS specimens of mixes A, B and C respectively. The final value is predicted from the equation $S_t = t/(at + b)$ derived by the method of least square by using the data up to the age of three months, where S_t is shrinkage strain at the age t and a and b are constant values. The relationships between shrinkage and V/S ratio show hyperbolic curves as illustrated in Fig.11. Mix A in series I is the same as mix D in series II, while the final value (87×10^{-5}) of A stored in R.H. 60% air is about 60% greater than that (47×10^{-5}) of D stored in R.H. 70% air for the JIS specimens, and this reduction in shrinkage increases when the V/S ratio increases. The ratios of the final shrinkage of specimens having various V/S to that of the JIS specimen is shown in Fig.12. Thus the effect of the V/S value of a specimen (i.e. the effective thickness d_w) on the shrinkage can be obtained correlatively to the JIS specimen. For the ordinary reinforced concrete slab of highway bridges (V/S = 10cm), the shrinkage strain is about one half that of the JIS specimen, while in the Rüschi's equation (see Fig.3), the shrinkage strain for $d_w = 20\text{cm}$ (V/S = 10cm) is 75% of that for $d_w = 5\text{cm}$ (V/S = 2.5cm). Consequently the size effect shown by Rüschi cannot be used directly to predict the shrinkage of slabs from the value measured by the JIS

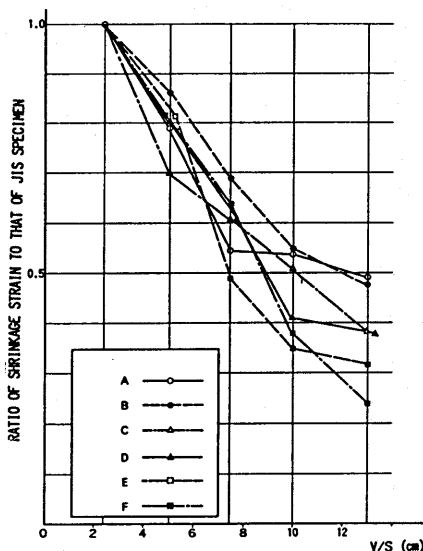


Fig.12 Relationships between V/S and the ratio of shrinkage to that of JIS specimen

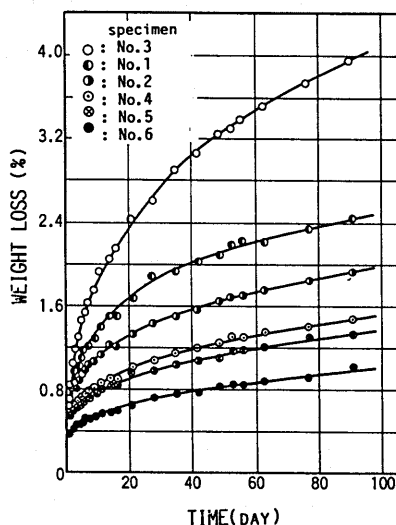
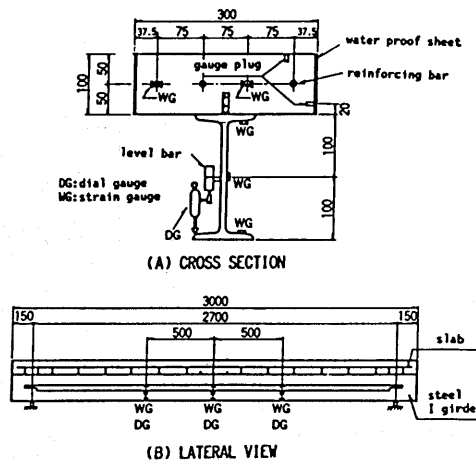
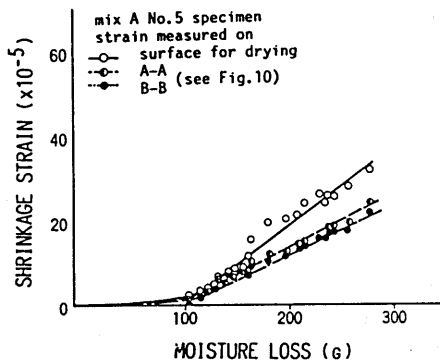


Fig.13 Relationships between time and weight loss of the specimen (mix A)



test. **Fig.13** illustrates the relationships between the weight loss of the specimen and the drying age for the concrete mix **A**. **Fig.14** shows the relationships between moisture loss (weight loss) and shrinkage strain for mix **A**. It is confirmed that moisture loss at the initial stage of drying does not contribute to shrinkage strain.

4.2 Model Girder Test

(1) Outline of the Test

A model girder test was carried out in order to examine the applicability of the analytical method used in **section 3** and to reproduce experimentally the mechanism of the deterioration of the slab due to shrinkage. Mix proportions used in the test are listed in **Table 6**. Mix **CC** is a mix commonly used in the Kansai area. In order to prevent shrinkage cracks in addition to mix **CC**, 4 kinds of mixes were examined in this test; mix **HWRC** with a high water reducing agent to reduce the unit water content, mix **SFRC** with steel fibers to resist the shrinkage cracks, mix **EXC** with expansive cement to compensate for the shrinkage strain, and mix **LC** containing lightweight aggregate with low elastic modulus in which shrinkage cracks had not been observed in the field investigation.

The details of the model girders are shown in **Fig.15**. In the slab (flange), deformed bars of 4xD13 for No.I girder and 4xD16 for No.II girder were arranged to examine the effect of longitudinal bars. Both side surfaces of the flange concrete were sealed with waterproof sheets(see **Fig.15**). Deflections, and

Table 6 Mix proportions and properties of concrete

mix	max. size of (mm)	slump (cm)	air (%)	W/C (%)	S/a (%)	unit content(kg/m ³)(x9.8kN/m ³)						properties of concrete(kg/cm ²)(x98kPa)						
						W	C	S		G	add.	WRA	f _{cu}	f _{ca}	f _{tw}	f _{ta}	E _{cu} x10 ⁵	E _{ca} x10 ⁵
								S1*	S2*									
CC	20	9.5	3.7	50	42	180	360	210	500	1047	---	Po*	414	---	34.0	---	31.8	---
HWRC	20	9.5	3.8	50	44	157	314	241	555	1061	---	M1*	416	---	31.0	---	34.8	---
SFRC	20	10.0	4.0	50	55	203	406	270	617	766	Sf*: 79	Po	489	398	40.8	36.1	30.7	27.9
LC*	15	12.0	4.3	50	38	151	302	528*	578*	---	---	Po	290	272	19.3	16.1	17.0	16.1
EXC	20	9.5	3.8	50	42	175	320	221	505	1069	ec*: 30	Po	418	351	34.8	27.4	31.9	28.8

note: $f_{w_c}, f_{c_a}, f_{w_t}, f_{c_t}, E_{w_c}$ and E_{c_a} are compressive and tensile strengths and elastic moduli obtained at the age of 28 days by the specimens cured in water and in air respectively.

sf: steel fiber, ex: expansive cement, Po: air-entraining water reducing agent, Mi: High water reducing agent

S1: crushed sand, S2: sea sand, In LC mix lightweight aggregates were used for both fine and coarse aggregates.

strains of the reinforcing bars and of the steel girder were measured by electric strain gauges on the mid span and on the two sections 50cm apart from the mid span. Concrete strains were measured by a contact strain gauge on the upper and lower surfaces of the flange at the mid span. The flange concrete was demoulded one day after casting, and sealed with a vinyl sheet for 7 days, then dried at 20°C with R.H. 60%. A specimen of 12x30x40cm was used to measure free shrinkage strain for each mix, and its V/S value was adjusted to equal that of the model girder by sealing its side surfaces by waterproof sheets.

(2) Results and Discussions

Fig.16 shows the relationships between free shrinkage strain and age obtained by the 12x30x40cm specimens. Fig.17 shows the mid span deflections of No.II girders, and Fig.18 illustrates the strains measured at the mid span of the No.II girders of CC and LC as typical examples. Solid lines in Fig.17 and Fig.18 are the theoretical values obtained by the method described in section 3, and the base value ϕ_{fo} of flow written by each curve in Fig.17 was used so that the curve agreed most closely with the measured deflections. The test results can be summarized as follows.

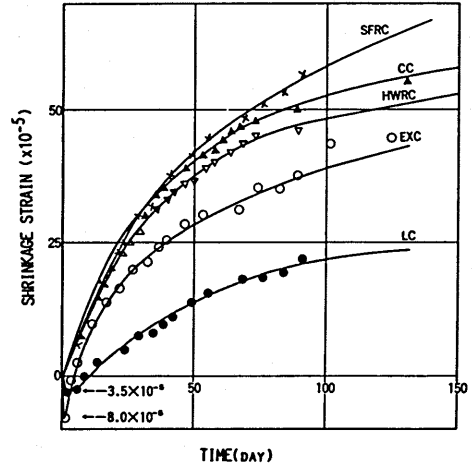


Fig.16 Free shrinkage strain for each mix

(i) Shrinkage Strain

Noticeable difference between the mixes was observed in the free shrinkage test (see Fig.16). The measured strains at the age of 90 days were 50 , 55 and 45×10^{-5} for CC, SFRC and HWRC respectively. This is mainly due to differences in their unit water contents. EXC and LC expanded once at the first stage, and then shrank. The measured strains at 90 days were 35 and 20×10^{-5} respectively, much less than that of CC.

(ii) Deflection of the Model Girder

The deflections of SFRC and HWRC girders were greater than that of CC girder. For SFRC girder, this is because the shrinkage strain was greater than that of CC, but, for HWRC girder, though its shrinkage was smaller, its deflection was larger than that of CC. It is presumed for the latter that the smaller volume of cement paste used in HWRC mix produced higher rigidity and smaller creep as compared with CC. The deflections of EXC and LC girders were smaller than that of CC girder because of their small shrinkage strain, and it is remarkable that in LC girder, deflection was one third of CC girder because of the additional effect of its low elastic modulus.

The analytical results agreed well with the test results when the base value ϕ_{fo} of flow of 2.0 for CC, SFRC and RC and 1.0 for HWRC were used. This method, however, could not be used to analyze the EXC girder, because there were no available data on the relationship between properties of concrete, expansion and constraint. The effect of the steel ratio of the slab is shown in Fig.19 for No.I and II girders of CC, in which steel ratios were 1.7% for No.I and 2.6% for No.II, and the analysis could estimate well this effect.

(iii) Strains of the Girder

As illustrated in Fig.18, the strains obtained by the analysis agreed well with the test results. It should be noted that the strains of LC girder were about one third of those of CC girder. It was found upon the inspection of the actual deck slab of Hanshin Expressway that the deterioration of the lightweight concrete slab was less serious than that of the normal concrete slabs. It is quite interesting that similar results were observed in both the in-situ and laboratory investigations.

(iv) Restrained Stress and Cracking

Restrained stresses on the bottoms of the slabs of the model girders (No.II) are shown in Fig.20. The drying ages when the restrained tensile stress attained the maximum value are 73, 73, 122, and 108 days for CC, HWRC, SFRC and LC girders respectively. The maximum tensile stress for each girder is greater than its tensile strength except LC girder, and it seems probable that shrinkage cracks will occur. In the model girder test, visible cracks on CC, HWRC and SFRC girders were observed at the ages listed in Fig.20. Fig.21 shows the

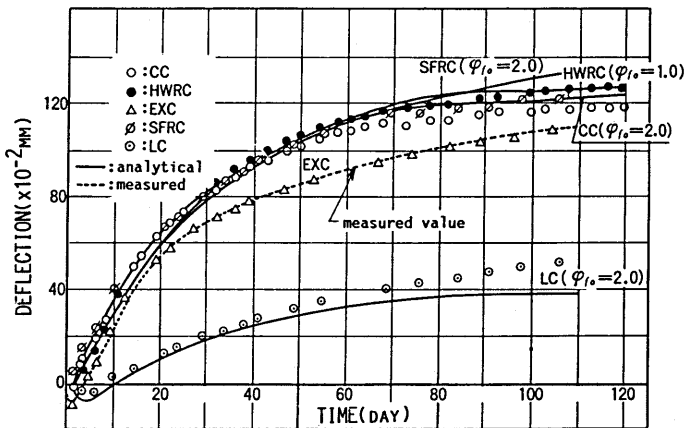


Fig.17 Mid span deflection for each girder

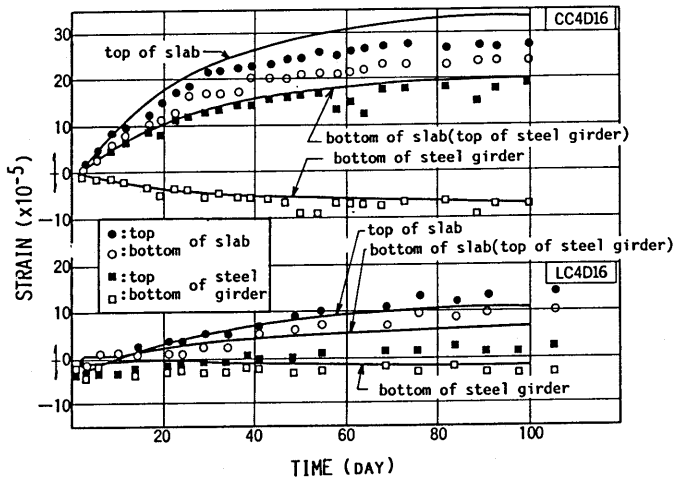


Fig.18 Mid span strains of CC and LC girders (No.II)

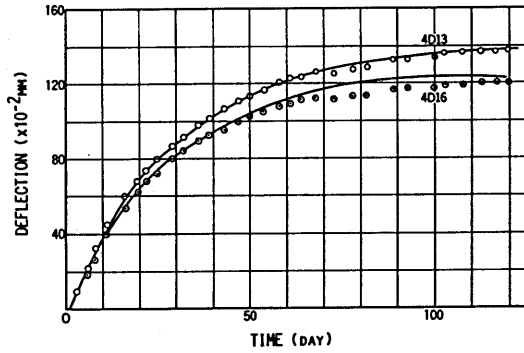


Fig.19 The effect of steel ratio on the deflection

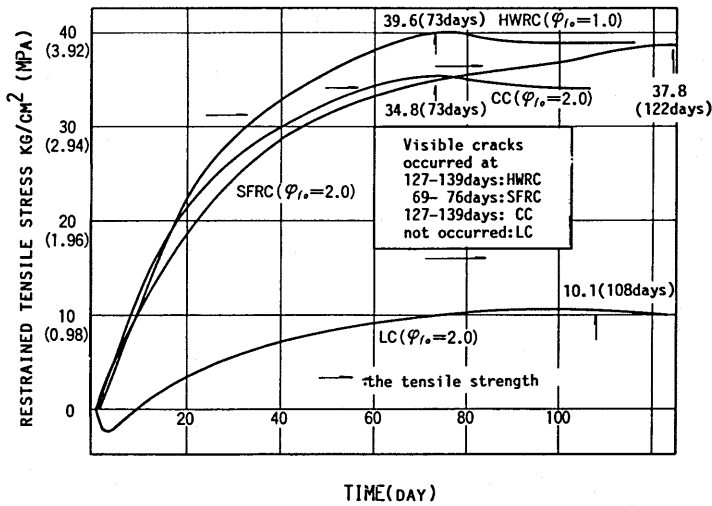


Fig.20 Restrained tensile stresses

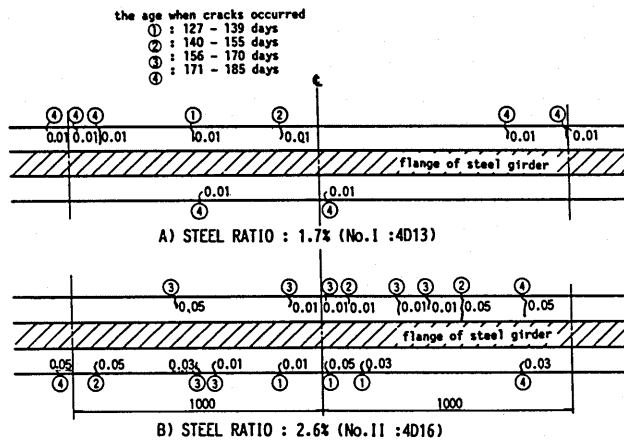


Fig.21 Observed crack patterns on the bottom surface

cracks on the bottom surface of **CC** girders; the density of the cracks and the ages at cracking are clearly affected by the steel ratios as predicted by the analysis. The age when the restrained tensile stress reached the tensile strength did not agree with the observed age because of the effects of sustained loading and development of strength ,etc, but differences between the observed and predicted ages are not so great and amount to about 50 days in both **CC** and **HWRC** girders. Therefore it can be predicted approximately by this analytical method whether shrinkage cracks will occur or not and when they will occur. In the model girder test cracks could not be found in **LC** and **EXC** girders even after 250 days.

5. CONCLUSIONS

In this study the deterioration of the reinforced concrete deck slabs of the steel highway bridges due to shrinkage of concrete was investigated. The following conclusions may be drawn.

(1) The cracking on the bottom surfaces of the slabs developed even before service, though no cracks had been observed at the time of demoulding. The development of the cracks continued up to the age of 2 or 3 years. It became clear that this phenomenon could be caused by the tensile stress due to constraint of shrinkage of concrete by the steel girder and the reinforcing steel in the slab.

(2) A theoretical method was developed in order to analyze the restrained stress by using a step-by-step integral scheme, and it was verified by the model girder test and by the field investigation

(3) The size effect of the specimen on shrinkage was examined experimentally in order to correlate the JIS test results with the actual structural concrete. It seems reasonable that half of the final shrinkage strain obtained by the JIS test should be used for the base value in R sch's equation when analyzing ordinary reinforced concrete slabs, the V/S value of which is about 10cm.

(4) The effect of steel ratio of the slab on constraint of shrinkage is considerable, and the restrained tensile stress was about 40% greater than that of slabs without reinforcing bars for the simply supported composite girder bridge. In design, therefore, the appropriate arrangement of reinforcing bars should be considered both to prevent the shrinkage cracks and to resist the slab moment.

(5) In the center span of the continuous girder bridge, the effect of reaction due to shrinkage was large enough for the restrained tensile stress to become twice that of the simply supported girder bridge.

(6) It became obvious from the model girder test that lightweight concrete and concrete with expansive cement were effective in preventing the shrinkage cracks.

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