- Technical Paper -

NUMERICAL SIMULATION OF THERMAL STRESS IN HIGHLY DURABLE RC SLAB ON PC COMPOSITE GIRDER BRIDGE

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ABSTRACT

A multiple protection highly durable concrete with blast furnace slag cement and expansive additive was applied in RC deck slab construction of Hikohei post tensioned bridge to mitigate deterioration and early age cracking risk of the restrained concrete slab. The present study has accurately simulated the early age volume changes of Hikohei bridge slab using 3D FEM model and conducted parametric studies utilizing the model in evaluating the effect of expansive additive, autogenous shrinkage and coefficient of thermal expansion on the risk of early age cracks in deck slabs.

Key Words: Blast Furnace Slag Cement, Expansive Strain, Autogenous Shrinkage, FEM Simulation

1. INTRODUCTION

The RC deck slab for 43.7m long Hikohei bridge with post-tensioned segments PC girder bridge in Fukushima prefecture was initially planned to be constructed with concrete using ordinary Portland cement. The RC bridge slabs of road infrastructures in cold regions of Japan are reported to be susceptible to severe deterioration due to combined frost damage, chloride attack, ASR and fatigue which are aggravated by early age thermal and shrinkage cracks[1]. Hence, a multiple protection highly durable RC slab with blast furnace slag cement, expansive additive, higher air content, and low water-binder ratio (Table 1) was proposed in the construction of Hikohei bridge deck slab (Fig. 1(a)). The highly durable Hikohei bridge slab was constructed in July 2017 adopting special construction and curing methods i.e., appropriate construction steps considering setting time of concrete, providing shades for preventing solar radiation upon newly placed concrete, 28 days wet curing with double layered curing sheets etc (Fig. 1(b)). Eventually, there were no signs of early age thermal and shrinkage cracks and consecutive deterioration observed on the Hikohei bridge RC deck slab.

In this context, the present study aims at simulating volumetric changes and thermal stresses in Hikohei bridge RC deck slab in FEM utilizing material properties obtained from laboratory investigations which will be verified by the measurement data from the real structure. Furthermore, the authors conducted parametric studies for evaluating the influence of expansive additive and coefficient of thermal expansion of concrete upon the occurrence of early age cracks due to restrained volume changes in RC bridge deck slabs.

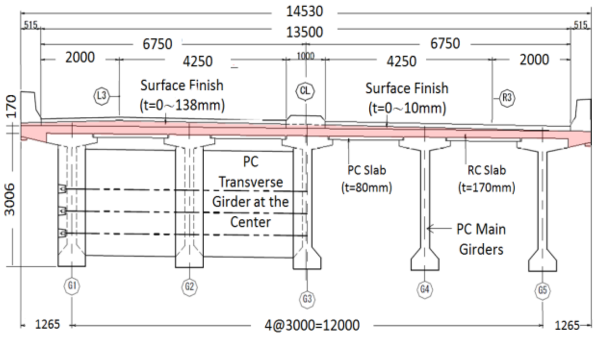

Fig. 1(a) Colored portions indicate the application of durable concrete for deck slab on Hikohei bridge

Fig. 1(b) Curing methods adopted for the deck slab

2. EXPERIMENTAL INVESTIGATIONS FOR MATERIAL PROPERTIES

The fundamental material properties such as time dependent compressive strength and Young's modulus development and free autogenous shrinkage of the proposed concrete mix were primarily evaluated by conducting material level investigations. At the same

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Table 1 Concrete mix proportion for Hikohei bridge slab and test specimens

Concrete Mix	W/B %	s/a %	Air %	Unit Weight (kg/m^3)						
				W	C	Ex	S1	S2	G1	AE+Ad
Hikohei Design Value	45	44.4	5.0±1.5	173	365	20	382	376	410	3.85
BB	45	44.4	5.9	165	385	20	382	376	410	3.85
BBEX	45	44.4	6.7	172	365	20	382	376	410	3.85

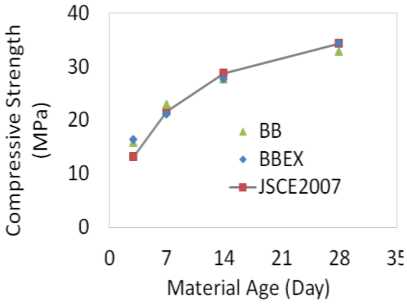


Fig.2(a) Compressive strength development

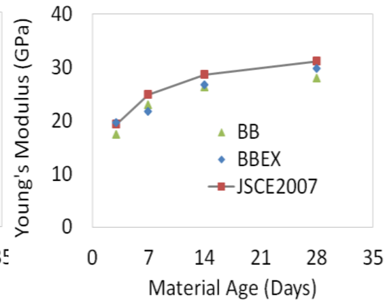


Fig.2(b) Young's modulus development

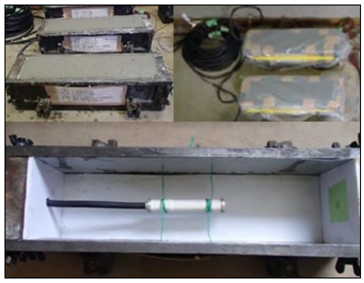


Fig. 3(a) Autogenous shrinkage specimens

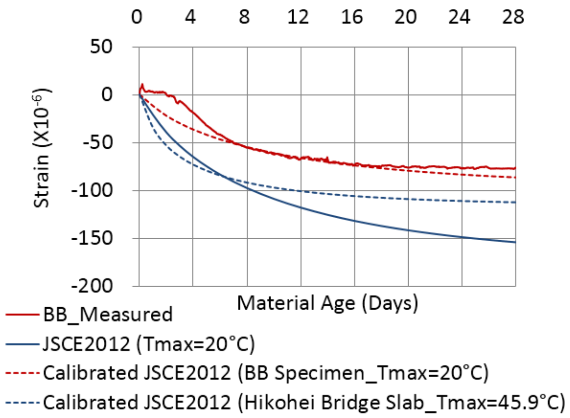


Fig. 3(b) Measured and calculated (modified JSCE2012 equation) autogenous shrinkage

time, proctor penetration test and N-type penetration tests were performed in the site for predicting the actual setting time in advance before the construction of real Hikohei bridge deck slab. The concrete mix with and without expansive additive (BB=Blast furnace slag cement concrete without expansive additive and BBEX=Blast furnace slag cement concrete with expansive additive) were considered in the test investigations to evaluate the compressive strength and Young's modulus development and free autogenous shrinkage of the proposed concrete.

2.1 Compressive Strength and Young's Modulus

Time dependent compressive strength and Young's modulus development (JIS A 1108) of BBEX and BB concrete appeared to be of similar trend as shown in Fig.2(a) and (b). Since JSCE2007[2] equation for time dependent compressive strength and Young's modulus development showed approximately good agreement with those of BB and BBEX, both equations (Eq.(1) and (2)) were applied in simulation of Hikohei bridge deck RC slab forward. Moreover, JSCE2007[2] time dependent equations for development of tensile strength (Eq.3) was also adopted in the stress analysis.

$$f_c'(t) = (t/(a+b.t)).d(i).f_{ck}' \quad (1)$$
$$E_c(t) = 4700.(f_c'(t))^{0.5} \quad (2)$$
$$f_{tk}(t) = 0.44.(f_c'(t))^{0.5} \quad (3)$$

Where, $f_c'(t)$ =time dependent compressive strength, $f_{tk}(t)$ = time dependent tensile strength, $E_c(t)$= time dependent Young's modulus, f_{ck}'= concrete design standard strength, a=6.2, b=0.93 and d(i)=1.15 for i=28 days. In the present study, 28th days strength obtained from the laboratory investigations were given input for f_{ck}'.

2.2 Free Autogenous Shrinkage

The free autogenous shrinkage specimens were made with BB concrete in 100×100×400 mm steel molds in sealed condition at 20ºC constant curing temperature. Free shrinkage strain was measured with a low stiffness strain gauge embedded in the center of each specimen (Fig.3(a)). The maximum value of the measured autogenous shrinkage is around 76×10^{-6} whereas the autogenous shrinkage equation (Eq.4 for blast furnace slag cement) recommended by 'JSCE Standard Specifications for Concrete Structures 2012'[3] considering the effect of maximum temperature produces larger value around 150 $X10^{-6}$ for BB concrete in 20°C constant curing temperature as shown in Fig.3(b). JSCE2012 autogenous shrinkage equation is as below

$$\varepsilon_{ag} = -\beta\varepsilon'_{as\alpha} \text{ x } (1\text{-exp }(\text{-a x }(t'\text{-}t_s)^b))$$
$$\varepsilon'_{as\alpha} = 2350 \text{ x exp }(-5.8 \text{ x } (W/C)) + \varepsilon'_{asT} \quad (4)$$
$$\varepsilon'_{asT} = 80 \text{ x } (1\text{-exp }(-1.210^{-6} \text{ x } (T_{max}-20)^4))$$

Where, β = coefficient indicates the influence of cement and admixture (β=1 for blast furnace slag cement), t' = effective material age, t_s = initial setting time, $\varepsilon'_{as\alpha}$ = final value of autogenous shrinkage, a, b = coefficient expressing the progressive characteristics of autogenous shrinkage, W/C=water cement ratio, ε'_{asT} = autogenous shrinkage contributed by maximum temperature and T_{max} = maximum concrete temperature.

Since JSCE2012 equation considering β=1 produces larger autogenous shrinkage, Eq.1 has been scaled down by setting β=0.56 to simulate the measured autogenous shrinkage from BB concrete at 20°C temperature. Thus, calibrated JSCE2012 equation (β=0.56) considering the concrete temperature effect on autogenous shrinkage has been utilized in further simulation of Hikohei bridge deck slab instead of directly applying measured autogenous shrinkage obtained from BB concrete specimen (Fig.3(b)).

2.3 Setting Time Test

Both Proctor and N-type setting time test were conducted with BBEX concrete under real environmental condition at the Hikohei bridge site confirming initial setting time as 4.05 hour (0.17 day) and final setting time as 5.18 hour (0.22 day). Measurement data and simulation results were considered from 0.17 day to ignore the unpredictable thermal expansion during the very early age before initial setting of concrete which may behave as a plastic material with a large coefficient of thermal expansion having large deformation characteristics.

3. FINITE ELEMENT MODELING

3.1 Simulation Software

In the present study, structural level numerical FEM simulation is conducted to simulate the early age (until 28 days of material age) restrained expansion and shrinkage behavior of RC slab in Hikohei bridge utilizing commercial finite element software (JCMAC3) . The thermal analysis is followed by the structural stress analysis. Three dimensional linear hexahedral isoparametric heat generating and non-heat generating solid elements were used for materials in thermal and structural analysis.

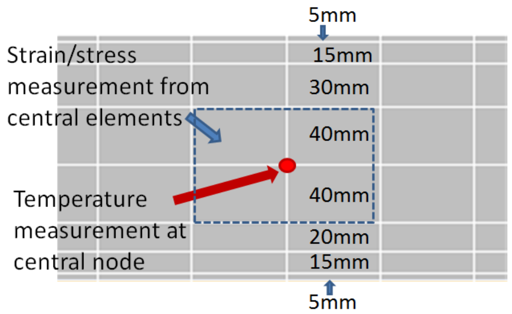
On the other hand, two-dimensional heat elements were pasted upon the heat transfer surfaces of the 3D solid material models to apply heat transfer boundary conditions. Additionally, reinforcing bars were modeled with one dimensional truss elements in longitudinal and transverse directions of the slab.

The material properties obtained from the laboratory investigations along with some parametric assumptions were considered in simulating the model. Finally, the full-scale simulation procedure was validated by the measured concrete temperature and volume change in Hikohei bridge RC slab.

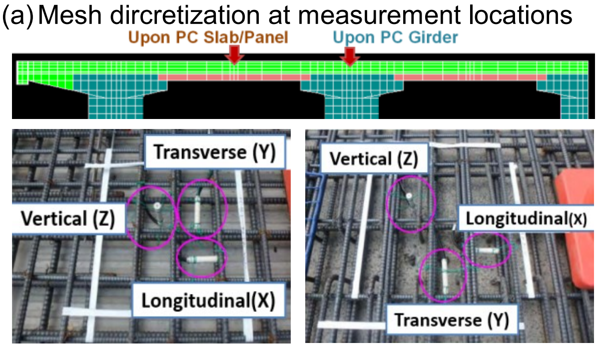
3.2 Structural Model of Hikohei Bridge

(1) Hikohei Deck Slab Construction and Field Measurement

Longitudinal (X, along bridge axis), transverse (Y) and vertical (Z) strains were measured in deck concrete upon PC girder and PC slab after concrete placement using embedded type strain gauges with thermocouples showed in Fig.4(a), (b) and (c). The measured longitudinal, transverse and vertical strains along with concrete temperatures were utilized to validate the FEM model for early age (until 28th days of curing) and the simulation procedure adopted in the present research.



(a) Mesh dircretization at measurement locations



(b) Upon PC Slab/Panel (c) Upon PC girder

Fig.4 Locations of embeded strain gauges in slab

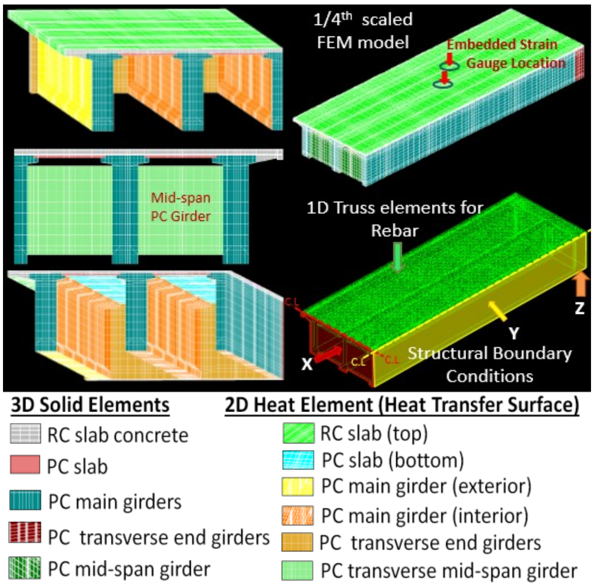


Fig. 5 Hikohei bridge FEM model

Table 2 Input heat transfer coefficients for Hikohei bridge heat transfer surfaces

Heat Transfer Surface	Heat Transfer Coefficient (W/m^2°C)
RC slab (top)	6
PC slab (bottom)	8
PC main girder (exterior)	14
PC main girder (interior)	10
PC transvers end girder	10
PC transverse mid-span girder	8

(2) Finite Element Model and Boundary Conditions

Hikohei post tensioned PC girder bridge consists of PC main girders, PC transverse end-girders, PC mid-span girder, PC slab (panels) and RC deck slab. As

Table 3 Input material properties for thermal and stress analysis for Hikohei bridge model

Properties	Deck Slab Concrete	Steel Bar	PC Girders	PC Slab
Heat Conductivity (W/m°C)	2.7	43	1.4	1.4
Specific Heat (kJ/kg°C)	1.15	0.47	1.15	1.15
Density (kg/m^3)	2300	7890	2300	2300
Initial Temperature (°C)	30.7	31	31	31
Young's Modulus (N/mm^2)	JSCE2007	2x10^5	36600	36600
Poisson's Ratio	0.2	0.3	0.2	0.3
Coefficient of Thermal Expansion (X10^{-6}/°C)	9.3	10	10	10

shown in Fig.5, RC deck slab was modeled with heat generating 3D solid elements whereas other components were modeled with non-heat generating 3D solid elements. The 1/4th portion of the simply supported Hikohei bridge was modeled with symmetric structural boundary conditions (Fig.5). Heat transfer coefficients for different heat transfer surfaces of the bridge were determined from parametric studies in thermal analysis considering the adopted curing methods (Fig.1(b)), exposure and location of the surfaces as summarized in Table 2. Thermal and some of mechanical properties for Hikohei slab concrete, PC girders and PC slabs are summarized in Table 3.

3.3 Input for Structural Stress Simulation

(1) Thermal Analysis Input

JSCE 2007[2] Adiabatic temperature rise model was considered in thermal analysis. The ambient temperature history presented in Fig.6(a) recorded at the Hikohei bridge site was given as input.

(2) Compressive strength, tensile strength, Young's modulus

JSCE2007[2] time dependent equations (Eq.1, Eq.2 and Eq.3) for compressive strength, Young's modulus and tensile strength development were adopted in the simulation as discussed in Section 2.1.

(3) Autogenous Shrinkage Strain

Calibrated JSCE2012_Hikohei Bridge Slab_T_{max}=45.9°C shown in Fig.3(b) is adopted in the simulation of Hikohei deck slab as discussed in Section 2.2.

(4) Expansion Strain Energy model

Expansion strain model based on the total energy conservation hypothesis [4] was adopted in the present study to simulate the expansion strain due to the application of expansive additive. The expansion strain energy is obtained from the Eq.5 as follows.

$$U(t_e) = U_{\infty}.\,(1\text{-exp}\,(\text{-}\,a\,(t_e\text{-}t_0)^b\,) \qquad (5)$$

Where, $U(t_e)$=total energy at effective concrete age t_e, U_{∞}=ultimate value of the total energy, a and b= coefficient indicating the influence of the type of cement on the progressive characteristics of total energy, t_o =effective material age at the beginning of expansion. The parameters have been fixed as U_{∞}= 110X10^{-6}, to=0.3, a=1.5 and b=1 for Hikohei bridge slab concrete conducting extensive parametric studies utilizing the strains measured along longitudinal (X), transverse (Y) and vertical (Z) axes.

(5) Creep Reduction Factors

The effect of early age creep of concrete was considered by reducing the Young's modulus of concrete at the age of temperature increasing and decreasing period as recommended in JSCE2007[2]. The creep reduction factor was defined as 0.73 until 3 days of concrete material age and 1.00 from 5 days of concrete material age same as the recommended values in JSCE2007[2].

4. THERMAL AND STRUCTURAL STRESS ANALYSIS RESULTS

4.1 Simulation of Temperature and Strain in Hikohei Slab Concrete

Fig.6(b) and (c) depict the satisfactorily good agreement between the simulated and measured temperature history of deck concrete upon PC slab and PC girder respectively.

Moreover, simulation of longitudinal and transverse strains exhibit substantially good agreement with the corresponding concrete strains measured upon PC slab and PC girder (Fig.7(a),(b) and Fig.8(a),(b). However, differences were observed in case of simulated vertical strains (Fig.7(c) and Fig.8(c)) seemingly caused by the larger input value of calibrated JSCE2012 autogenous shrinkage considering temperature effect compared to measured autogenous shrinkage (Fig.3(b)) in absence of vertical restraints

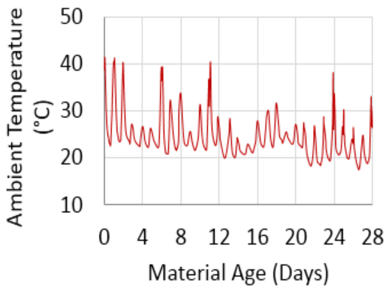


Fig. 6(a) Recorded ambient temperature at Hikohei bridge site

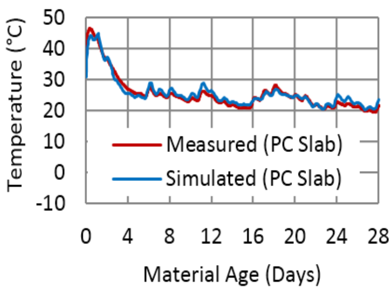


Fig. 6(b) Simulation of concrete temperature upon PC slab

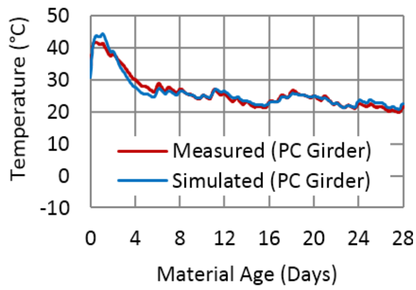


Fig. 6(c) Simulation of concrete temperature upon PC girder

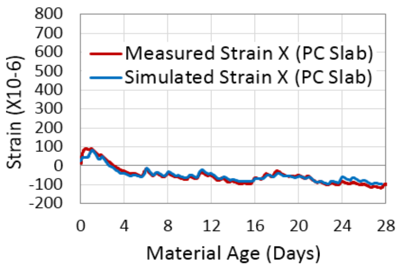


Fig. 7(a) Simulation of longitudinal (X) strain in concrete upon PC slab

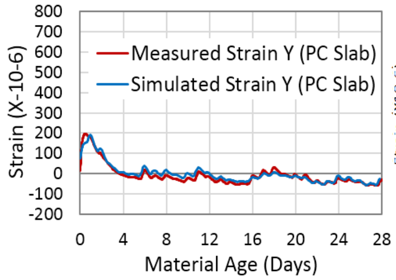


Fig. 7(b) Simulation of transverse (Y) strain in concrete upon PC slab

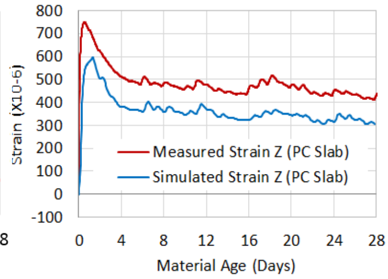


Fig. 7(c) Simulation of vertical (Z) strain in concrete upon PC slab

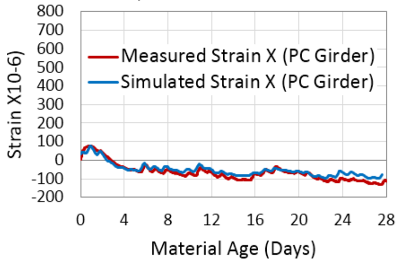


Fig. 8(a) Simulation of longitudinal (X) strain in concrete upon PC girder

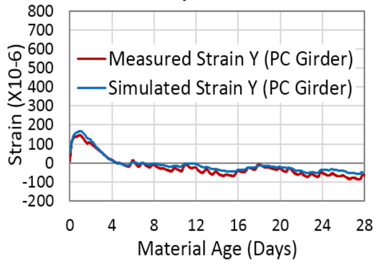


Fig. 8(b) Simulation of transverse (Y) strain in concrete upon PC girder

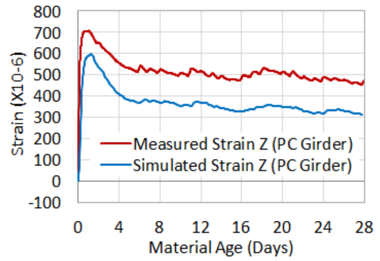


Fig. 8(c) Simulation of vertical (Z) strain in concrete upon PC girder

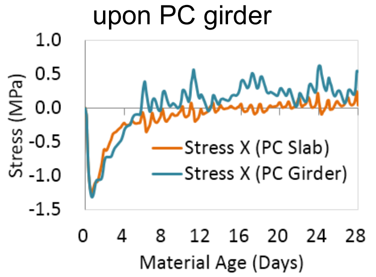


Fig. 9(a) Simulation of longitudinal stress in concrete

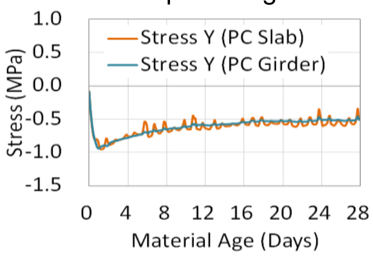


Fig. 9(b) Simulation of transverse stress in concrete

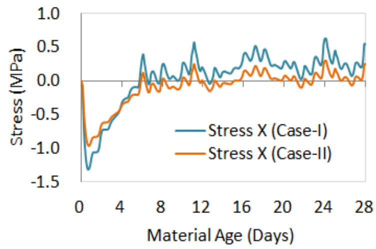


Fig. 9(c) Effect of C.R.F on concrete stress upon PC girder

due to reinforcing bars and underneath PC girders and slabs.

4.2 Simulation of Stresses and Parametric Studies

(1) Stresses in Hikohei Bridge Deck Slab

Since the concrete temperature and volumetric strains are well simulated for Hikohei bridge deck RC slab, generation of stresses in the deck concrete upon PC slab and PC girder were evaluated to determine the cracking risk in early age. Fig.9(a) and (b) demonstrate the simulated stresses generated along longitudinal (bridge axis) and transverse direction of the Hikohei deck slab. Maximum tensile stress generated along the bridge axis was 0.6 MPa whereas, there is no tensile stress generated along the transverses direction of the bride deck.

(2) Effect of Creep Reduction Factor

The effect of C.R.F. on the restrained strains was confirmed by parametric study. Analysis was carried out applying reduced value of C.R.F. i.e. 0.42 instead of 0.73 until the material age of 3 days and 0.65 instead of 1.00 from material age of 5 days of concrete. Fig.9(c) demonstrates that the reduced value of C.R.F. (Case-II) in early age has a considerable influence on reducing the simulated stresses in concrete compared to the JSCE2007[2] recommendation (Case-I) adopted in the Hikohei bridge model.

(3) Effect of Expansive Additive

The effect of expansive additive in reducing tensile stresses in RC slab is confirmed from the parametric study. The Hikohei bridge model was analyzed without considering the effect of expansive concrete. The maximum tensile stress in case of blast furnace slag cement without expansive additive is simulated as 1.91 MPa (Fig.10(a)) indicating greater risk of cracking than the Hikohei deck slab concrete.

(4) Effect of Autogenous Shrinkage

Previous researches revealed that autogenous shrinkage strain was relatively large while initial strength development rate was low for blast furnace slag cement[5]. Furthermore, autogenous shrinkage can be even larger at high temperature caused by hydration heat of cement inhibiting thermal and shrinkage cracks. However, Hikohei bridge concrete exhibited smaller value of autogenous shrinkage partially because the special curing methods were applied in the bridge deck construction. The effect of larger autogenous shrinkage (maximum value=$310X10^{-6}$) for blast furnace concrete (w/b=0.45, T_{max}=56°C) from Miazawa et.al.[6] was studied (stresses in concrete upon PC girders shown in Fig.10(b)).It is revealed that tensile stress can be as large as 3.0 MPa for larger autogenous shrinkage even though expansive additive has been used.

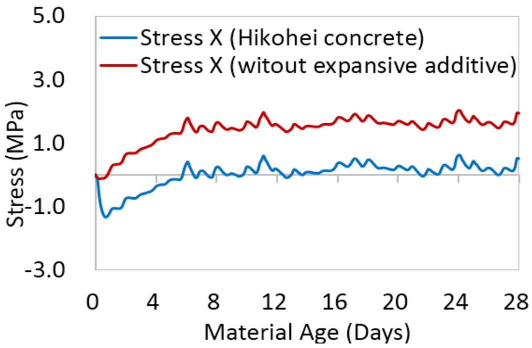


Fig. 10(a) Effect of expansive additive

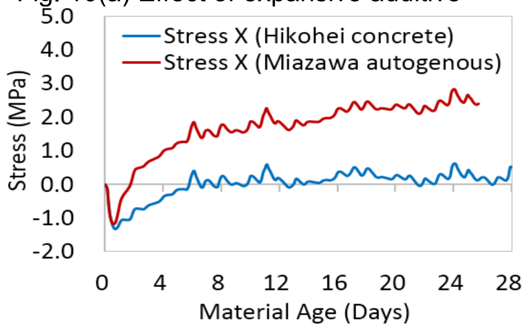


Fig. 10(b) Effect of Autogenous Shrinkage

(5) Effect of Coefficient of Thermal Expansion

Parametric studies were conducted utilizing the Hikohei bridge model to evaluate the effect of coefficient of thermal expansion (CTE) of PC girders/PC slabs and RC deck slab on the generation of tensile stresses. In Fig.11(a), CTEs of PC girders/PC slabs were varied keeping the CTE of RC deck slab constant ($9.3X10^{-6}$/°C). It reveals that lower value of CTE of restraining components increase the risk of cracking by increasing the tensile stresses in RC slab concrete. On the other hand, CTEs of RC deck slab were varied keeping the CTE of PC girders/PC slabs constant ($10X10^{-6}$/°C) showed in Fig.11(b) indicating that lower value of CTE for RC deck slab has lower risk of cracking. However, Fig.11(a) and 11(b) indicate that there was no significant effect on stress in compression zone (temperature increasing zone) with different coefficient of thermal expansion.

5. CONCLUSIONS

The following conclusions have been derived from the present study:

(1) The FEM simulation procedure followed in the present study was successfully verified in real structural level simulation of Hikohei bridge in terms of concrete temperature and early age thermal and volumetric strains in RC deck slab concrete. The calibrated expansion strain energy, autogenous shrinkage, appropriate utilization of creep reduction factors and coefficients of thermal expansion of concrete were the key factors for obtaining good agreements in the simulation.

(2) Simulation of stresses in Hikohei bridge model confirmed the lower cracking risk of Hikohei deck slab concrete mainly due to the low autogenous shrinkage and utilization of expansive additive.

(3) Parametric studies confirmed the considerable effect of the coefficient of thermal expansion of RC slab concrete and PC girders/PC slabs on the generation of tensile strength in the RC deck slab.

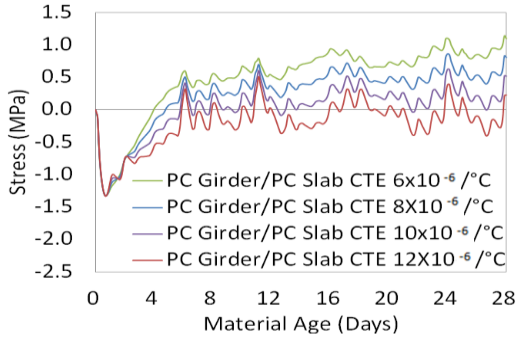


Fig. 11(a) Effect of CTE of PC girders/PC slabs on longitudinal stresses (upon PC girder)

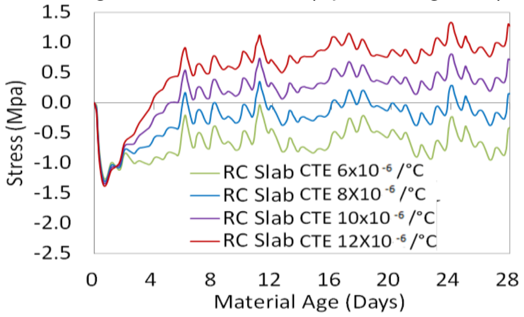


Fig. 11(b) Effect of CTE of RC deck slab on

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