Study on Prediction of Freeze-Thaw Cycles in Concrete Structural Members in Cold Regions*

by

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Abstract

The durability and service life of concrete structures are related to changes in the concrete surface temperature, which is an external deterioration factor, and the cycles of freezing and thawing that the changes induce. In this study, we predict the relationship between continuous changes in surface temperature about the freezing point and the cycles of freezing and thawing well below the surface, using a method of calculating freezing and thawing at a point below the surface and determining the calculation's accuracy based on changing boundary thermal conditions, which are related to solar irradiation and so on.

1. INTRODUCTION

The durability and a service life of concrete in a cold marine environment are related to frost deterioration according to the cycles of freezing and thawing and to reinforcing steel corrosion resulting from chloride ions from the sea [1]. In this study, the frost damage arising during, before, and after winter is studied as one of the deterioration factors in cold marine environments. The cycles of freezing and thawing in concrete depend on the size and form of the member and on the depth from the surface. It is necessary to determine the cycles as experienced at the center of the structural member and at each point below the surface. In order to grasp the service life, design the mix for durability, and repair and reinforce the structure through maintenance and management. Present specifications, however, do not consider the relationship between the size of a member and its durability in a clear manner [2].

The authors have analyzed three-dimensional structural members by a conventional

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method [3], a numerical analysis using the differential method, in order to estimate the thermal distribution and depth of freezing to sufficient accuracy [5]. Further we have made column specimens, which are general common members in concrete structures, and determined the accuracy of the analysis using these three-dimension models. The range of three-dimensional effects and the limits of validity of two-dimensional analysis have also been investigated [6].

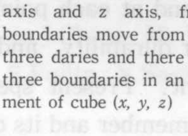
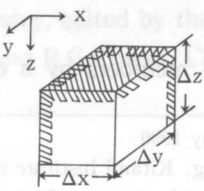
In this study, the relationship between changing surface temperature around the freezing point and the cycles of freezing and thawing at points below the surface is investigated, and a method of calculating the freeze-thaw cycles at each depth is studied.

2. METHOD

2.1 Method of Analysis

Conventional analysis is used, based on a differential method. The equation used and

Table 1 Method of analysis

Case	Explanation and Shape of element	Analytical equation
Two dimensional	In freeze processing from two directions of *x* axis and *y* axis, frost boundaries move from the two directions and there are two boundaries in an element of square (*x, y*) 	$T_{x,y}^{p+1}=T_{x,y}^{p}$ $+\frac{kg_i\Delta t}{(\Delta x)^2}(T_{x-1,y}^{p}-2T_{x,y}^{p}+T_{x-1,y}^{p})$ $+\frac{kg_i\Delta t}{(\Delta y)^2}(T_{x,y-1}^{p}-2T_{x,y}^{p}+T_{x,y+1}^{p})$ $(i=1:\ T_{x,y}^{p}<T_f,\ i=2:\ T_{x,y}^{p}>T_f)$ Latent heat of fusion: $\Delta H^k=\frac{\Delta t}{(\Delta y)^2}\{\lambda_1(T_{x,y}^{p}-T_{x-1,y}^{p})+\lambda_2(T_{x,y}^{p}-T_{x+1,y}^{p})\}$ $+\frac{\Delta t}{(\Delta y)^2}\{\lambda_1(T_{x,y}^{p}-T_{x,y-1}^{p})+\lambda_2(T_{x,y}^{p}-T_{x,y+1}^{p})\}$ $T_{x,y}^{p+1}=T_{x,y}^{p}=T_f$
Three dimensional	In freeze processing from three directions of *x axis, y* axis and *z* axis, frost boundaries move from the three daries and there are three boundaries in an element of cube (*x, y, z*) 	$T_{x,y,z}^{p+1}=T_{x,y,z}^{p}$ $+\frac{kg_i\Delta t}{(\Delta x)^2}(T_{x-1,y,z}^{p}-2T_{x,y,z}^{p}+T_{x+1,y,z}^{p})$ $+\frac{kg_i\Delta t}{(\Delta y)^2}(T_{x,y-1,z}^{p}-2T_{x,y,z}^{p}+T_{x,y+1,z}^{p})$ $+\frac{kg_i\Delta t}{(\Delta y)^2}(T_{x,y,z-1}^{p}-2T_{x,y,z}^{p}+T_{x,y,z+1}^{p})$ $(i=1:\ T_{x,y,z}^{p}<T_f,\ i=2:\ T_{x,y,z}^{p}>T_f)$ Latent heat of fusion: $\Delta H^k=\frac{\Delta t}{(\Delta x)^2}\{\lambda_1(T_{x,y,z}^{p}-T_{x-1,y,z}^{p})+\lambda_2(T_{x,y,z}^{p}-T_{x+1,y,z}^{p})\}$ $+\frac{\Delta t}{(\Delta y)^2}\{\lambda_1(T_{x,y,z}^{p}-T_{x,y-1,z}^{p})+\lambda_2(T_{x,y,z}^{p}-T_{x,\hat{y}+1,z}Z^{p})\}$ $+\frac{\Delta t}{(\Delta Z)^2}\{\lambda(T_{x.y.z}^{p}-T_{x.y.z-1}^{p})$ $+\lambda_2(T_{x.y.z}^{p}-T_{x.y.z+1}^{p})\}$ $T_{x,y,z}^{p+1}=T_{x,y,z}^{p}=T_f$

the definition of elements are shown in Table 1 [4]. The surface temperature of the specimen is input as a boundary condition and the temperature within the specimen is calculated by a differential method. The conditions of the analysis, which are the same for both experimental specimens and the theoretical work, are those used in our past studies [4, 5], as shown in Table 2. The frost temperature is assumed to be -1.3 based on historical studies [7].

Table 2 Conditions of analysis

Case		Three dimensions	
Condition of layer		Frozen	Unfrozen
Thermal conduction rate: k(kcal/mhr°C)		3.64	2.13
Specific heat: Cc(kcal/kg°C)		* 2	* 2
Thermal diffusion rate: kg(m^2/hr)		0.00510 * 3	0.00350 * 4
Density: ρ(kg/m^3)		2400	
latent heat of fusion * 1: L(kcal/kg)		4.5	
Freezing point T_f(°C)		−1.3	
Water Content	R_v(%/vol)	13.5	
	R_w(%/wt) * 5	4.60	

Note *1: Converted to unit weight of concrete
*2: Cc=715/ρ according to JSCE concrete standards
*3: notes KS
*4: notes KL
*5: notes GAN

2.2 Calculation of the Moving Boundary between the Frost Phase and Non-Frost Phase

The flow was studied in order to determine the boundary between the frost and non-frost phases. The latent heat of each element, next other one within 10 elements and one before 10 notches calculation time were calculated. And a state quantity was defined. It is unity (1) when the element is in the frozen state and zero in the thawed phase.

2.3 Simulation Test Specimens

The concrete mix proportion of the simulational specimens is shown in Table 3. The size and shape of the specimens is shown in Fig. 1. The calculation covered a one-eighth portion of the specimens, since the specimens have a point of symmetry and the boundary conditions are axially symmetrical.

Table 3 Mix proportion and properties of fresh concrete

W/C (%)	s/a (%)	Specified mix (kg/m^3)					Slump*	Air Content*
		Water	Cement	Fine Aggregate	Coase Aggregate	AE agent (cc)	(cm)	(%)
45	31	152	338	564	1277	101.4	12.5	4.5

Note *: Before casting

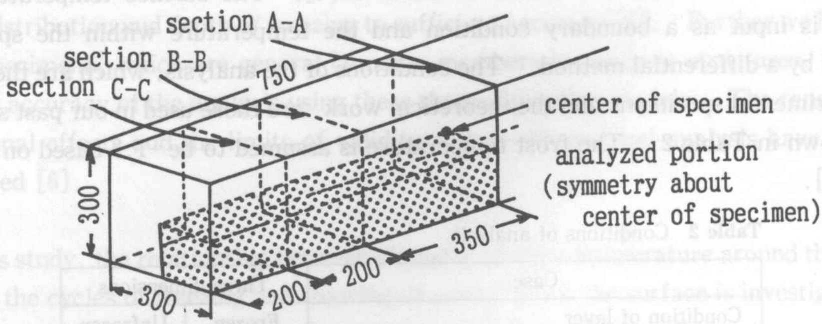


Fig. 1 Size and shape of column specimens

3. RESULTS OF ANALYSIS AND DISCUSSION

3.1 Results of Analysis

3.1.1 Results of two- and three-dimensional analysis

As shown Fig. 2, at the center section of the 75 cm member, the calculation by two dimensional analysis gave a result close to that by three-dimensional analysis and to the actual measured temperature. The thermal distribution across the section of a simulational specimen is shown in Fig. 3. The part of elements shape disturbed is the boundary between the frozen and thawed phases and the layer of latent heat generating, in this Figure.

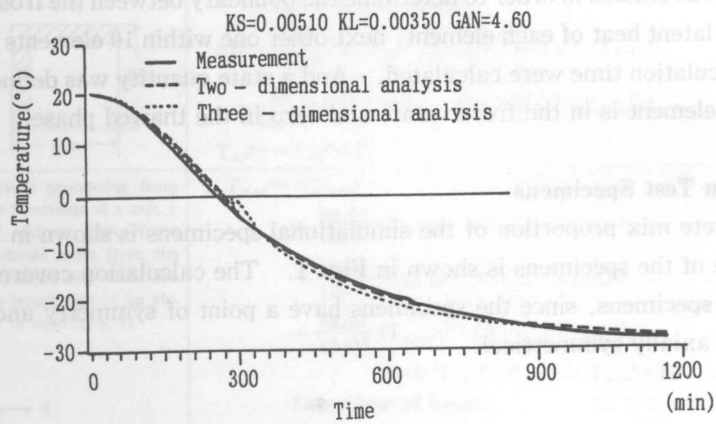


Fig. 2 Accuracy of analysis

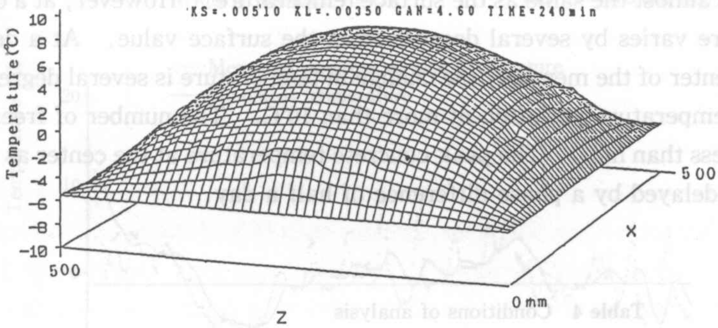


Fig. 3 Thermal distribution across section of specimen

3.1.2 The limit of validity of two-dimensional analysis

In order to determine the limit of validity of the two-dimensional analysis, the results of a simulation covering the changes in concrete surface temperature over a cycle at one day are shown in Fig. 4. The depth at which the temperature becomes free of the influence of three-dimensional changes and surface thermal changes is 40 cm below the surface.

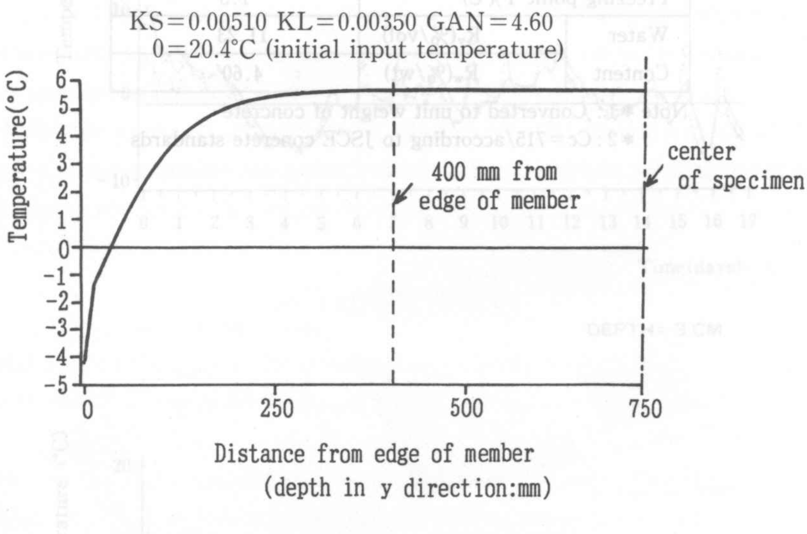


Fig. 4 Limit of validity of two-dimensional analysis

3.1.3 Simulation using measured surface temperatures

(1) Results of simulation

It is assumed that the section is 80 cm × 80 cm and that the axial length is sufficient to allow thermal effects from the ends to be ignored. The conditions of simulation are shown in Table 4. The boundary conditions, which are the concrete surface temperatures on the Japan Sea coast of Hokkaido in December, are input. The changes in temperature at each depth are calculated. The simulation results are shown in Fig. 5. At a depth of 3 cm, the temperature is almost the same as the surface temperature. However, at a depth of 15 cm, the temperature varies by several degrees from the surface value. At a depth of 40 cm, which is the center of the member, the change in temperature is several degrees only in spite of a surface temperature variation of more than 10°C. The number of freeze-thaw cycles is reduced to less than half. The peak concrete temperature at the center as compared with the surface is delayed by a phase difference of half a day.

Table 4 Conditions of analysis

Case		Two dimensions	
Condition of layer		Frozen	Unfrozen
Thermal conductivity : k(kcal/mhr °C)		3.64	2.13
Specific heat : Cc(kcal/kg°C)		＊2	＊2
Thermal diffusion rate : kg (m^2/hr)		0.00510	0.00350
Density : ρ(kg/m^3)		2300	
Latent heat of fusion＊1 : L(kcal/kg)		3.56	
Freezing point T_f(°C)		−1.3	
Water	R_v(%/vol)	11.23	
Content	R_w(%/wt)	4.60	

Note ＊1 : Converted to unit weight of concrete
＊2 : Cc=715/according to JSCE concrete standards

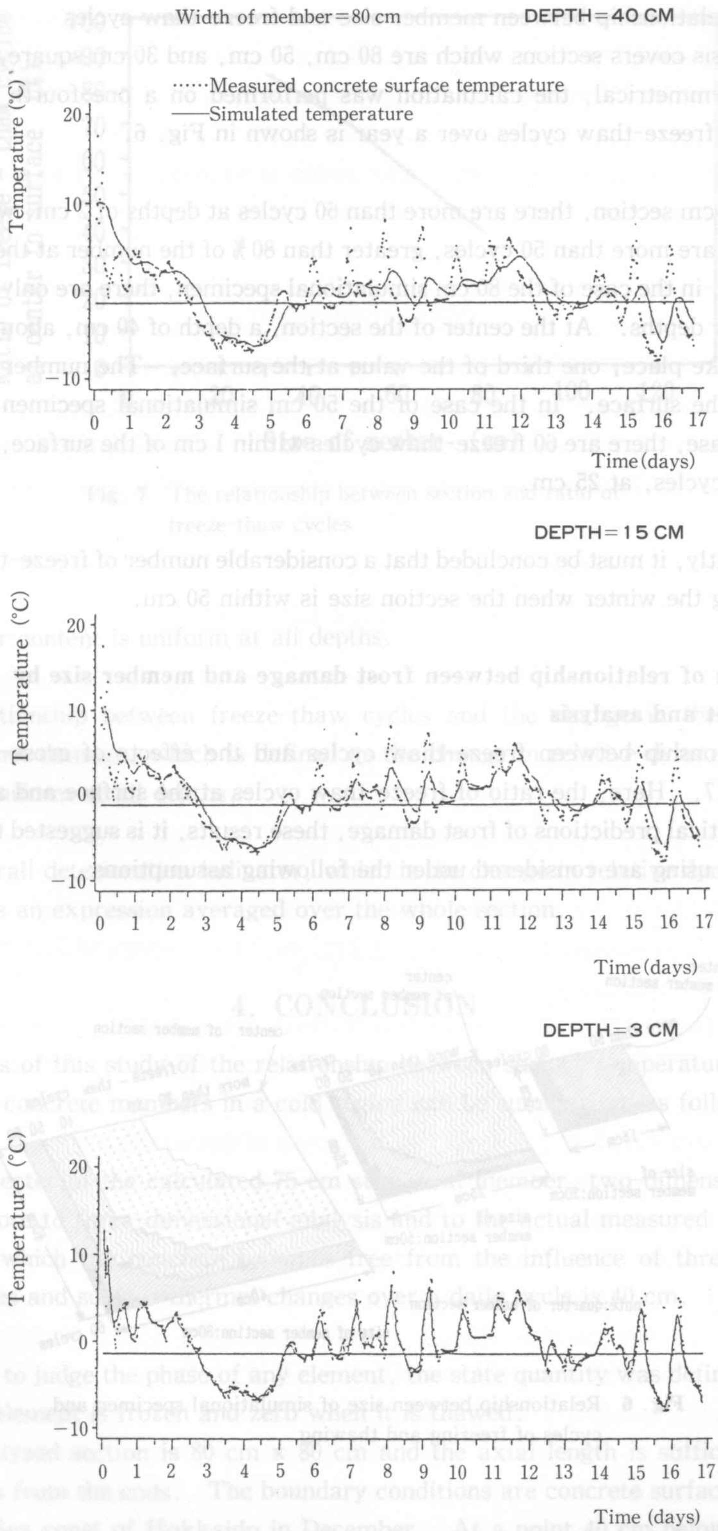


Fig. 5 Simulation of thermal distribution in concrete

(2) Study of relationship between member size and freeze-thaw cycles

The analysis covers sections which are 80 cm, 50 cm, and 30 cm square. Because the sections are symmetrical, the calculation was performed on a one-fourth section. The distribution of freeze-thaw cycles over a year is shown in Fig. 6.

For the 30 cm section, there are more than 60 cycles at depths of 2 cm, while at a depth of 15 cm there are more than 50 cycles, greater than 80 % of the number at the surface. On the other hand, in the case of the 80 cm simulational specimen, there are only 60 cycles even at very shallow depths. At the center of the section, a depth of 40 cm, about 20 freeze and thaw cycles take place, one third of the value at the surface. The number drops to 50 %, 20 cm below the surface. In the case of the 50 cm simulational specimen, which is the intermediate case, there are 60 freeze-thaw cycles within 1 cm of the surface, but two thirds of this, or 40 cycles, at 25 cm.

Consequently, it must be concluded that a considerable number of freeze-thaw cycles are suffered during the winter when the section size is within 50 cm.

3.2 Discussion of relationship between frost damage and member size by experiment and analysis

The relationship between freeze-thaw cycles and the effects of cross-section size is shown in Fig. 7. Here, the ratio of freeze-thaw cycles at the surface and at the center is used. In practical predictions of frost damage, these results, it is suggested that the effects of section size using are considered under the following assumptions:

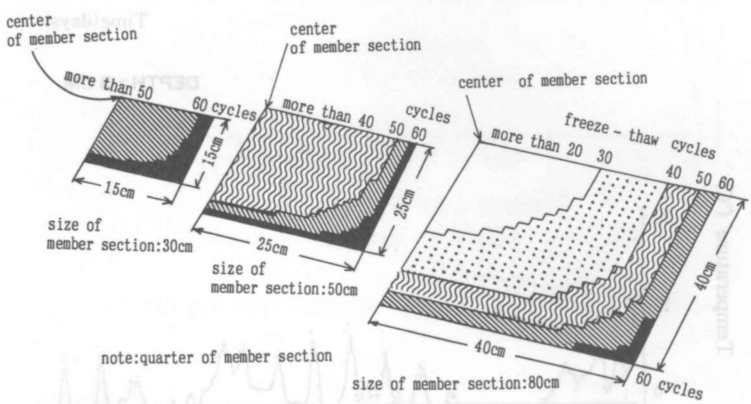


Fig. 6 Relationship between size of simulational specimen and cycles of freezing and thawing

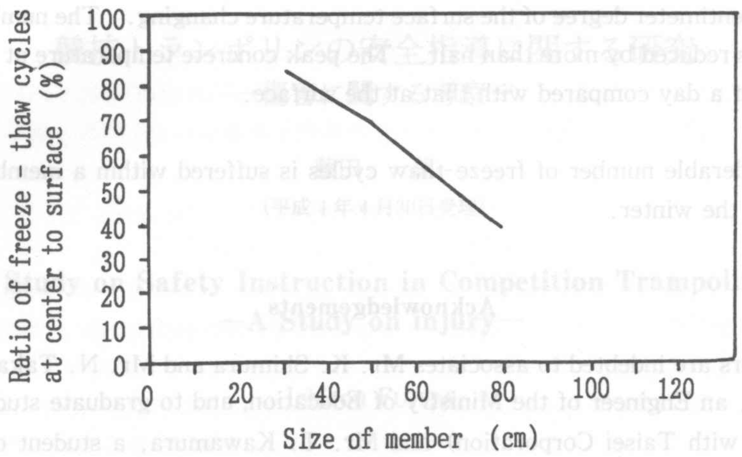


Fig. 7 The relationship between section and ratio of freeze-thaw cycles

(i) The water content is uniform at all depths.

(ii) The relationship between freeze-thaw cycles and the change in the deterioration indicator of frost damage, which is defined as the change in relative dynamic modulus of elasticity, is uniform at all depths.

(iii) The overall deterioration indicator, which is the change in relative dynamic modulus of elasticity, is an expression averaged over the whole section.

4. CONCLUSION

The results of this study of the relationship between surface temperature and freeze-thaw cycles in concrete members in a cold region can be summarized as follows.

1) At the center of the calculated 75 cm structural member, two-dimensional analysis gave results close to three-dimensional analysis and to the actual measured temperatures. The depth at which the concrete becomes free from the influence of three-dimensional thermal changes and surface thermal changes over a daily cycle is 40 cm.

2) In order to judge the phase of any element, the state quantity was defined to be unity (1) when the element is frozen and zero when it is thawed.

3) The analyzed section is 80 cm x 80 cm and the axial length is sufficient to ignore thermal effects from the ends. The boundary conditions are concrete surface temperature on the Japan Sea coast of Hokkaido in December. At a point 40 cm below the surface, which is the center of the member, the change in temperature is only several degrees despite

more than 10 centimeter degree of the surface temperature changing. The number of freeze-thaw cycles is reduced by more than half. The peak concrete temperature at the center is delayed by half a day compared with that at the surface.

4) A considerable number of freeze-thaw cycles is suffered within a member of 50 cm section during the winter.

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