Effects of a Lift Height on the Thermal Cracking in Wall Structures

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ABSTRACT

Once a structure fabricated with mass concrete is in a form of wall such as retaining wall, side walls of a concrete caisson and so on, cracks induced by hydration heat have been known to be governed by exterior restraints which are mainly related to the boundary conditions of the structure. However, it is thought that the degree of restraints can be alleviated considerably only if a lift height of concrete placement or a panel size of the wall is selected properly before construction. As a way of minimizing thermal cracking commonly observed in massive wall-typed structure, this study aimed at evaluating effects of geometrical configuration on the temperature rise and thermal stress through parametric study. Evaluation of the effect was also performed for cement types using anti-sulphate cement, blast furnace slag cement and cement blended with two mineral admixture and one ordinary Portland Cement, so called ternary blended cement.

As a result of analytical study, it was found that a lift height of concrete placement is the most important factor in controlling thermal cracking in massive wall, and the increase of a lift height is not always positive to the crack occurrence as not expected.

Keywords : mass concrete, wall, hydration heat, exterior restraints, interior restraints, a lift height, temperature, thermal stress, cement, thermal cracks

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1. Introduction

Recently, as structures built with concrete become massive and high strengthened, there is a trend to apply larger unit amount of cement than previous[1,2]. This tendency would cause occurrence of undesirable cracks due to excessive hydration heat during construction and eventually accompany durability and stability problems of the structure. Therefore, a comprehensive study for the control or prevention of these problems is significantly required.

This study has objectives of developing the analytical program to be able to evaluate a heat of hydration and thermal stress developed in the early mass concrete, and then providing with a method capable of minimizing thermal problems which may possibly occur during mass concrete working. Side walls of a caisson, which is a foundation of anchorage in Kwang Ahn Grand Bridge, was selected as an object of this study. Kwang Ahn Grand Bridge is a type of suspension and the anchorage and concrete caisson, one of major parts, play an important role of supporting all of loads transferred from superstructure. What it has to behaves structurally can differ from a generally known massive structure such as dams or nuclear power plants which only sustain the structural stability by its weight. In the case of general mass concrete, excessive heat of hydration can be controlled by employing larger sizes of aggregate or lower amount of cement than conventional concrete, But these specific massive structures should be additionally considered with respect to durability associated with environmental condition where the structure is to be built as well as the structural roles. Therefore, it is necessary to find an optimized construction method capable of preventing from crack occurrence as thoroughly as possible, under the condition that same amount of cement and aggregate sizes as ordinary concrete structure have to be applied.

In this study, effects of cement types on the thermal stress and hydration heat were evaluated first as one of ways to reduce temperature rise in a view of material control, and then a method of improving construction in massive walls was suggested throughout a relationship between thermal factors and thicknesses, lengths and a lift heights of concrete placement.

2. Material Criteria for The Finite Element Analysis and Modelling

2.1 Material Properties

Temperatures and thermal stresses measured from mass concrete become various according to material properties and environmental conditions[3].

Table 1 Physical characteristics of cement

Cement	Specific gravity	Blaine (cm^2/g)	Setting time (hr)		Stability
			initial	final	
Anti-sulphate cement	3.17	3,190	5:00	8:40	0.01
B.F. slag cement	3.05	3,830	4:50	6:40	0.03
Ternary blended cement	2.85	4,080	5:25	8:45	0.02

Table 2 Mix proportion

Design strength (kgf/cm^2)	Cement type	W/C (%)	s/a (%)	Unit weight (kg/m^3)					
				water	cement	sand	gravel	AE admixture	SP admixture
240	Anti-sulphate	43	49	155	360	877	947	0.1188	2.52
	B.F. slag	50	45	162	324	809	1025	0.0972	2.268
	Ternary blended	50	45.6	160	320	817	975	0.128	2.70

In this study, thus, three different types of cements such as anti-sulphate Portland cement (Type V), blast furnace slag cement and ternary blended cement were employed. Material characteristics of these cements for thermal analysis are shown in Table 1.

A program developed for the analysis of temperature and thermal stress was designed to input material characteristics and boundary conditions. Among material characteristics, maximum temperature rise (K) and reaction speed (α) were obtained from adiabatic temperature rise tests. And elastic modulus, compressive and tensile strength were calculated from the concept of concrete maturity. Mix design proportions for this study are shown in Table 2 and thermal parameters for each concrete are listed in Table 3.

2.2 Modelling for Finite Element Analysis

In general, since the wall has long length in compare with thickness, the cause of crack development is significantly affected by exterior restraints rather than interior ones[4,5,6]. Therefore, there is a tendency that cracks in walls would be generated since 2 to 3 weeks after concrete placement and penetrate through its thickness, which is known to be harmful effect to the structural integrity and safety. However, it is expected that the degree of exterior restraints be reduced only if thickness of the wall and a lift height increase.

Table 3 Input data of the program for thermal analysis

Input item		Anti-sulphate	B.F. slag	Ternary blended	Bed rock
Adiabatic temperature rise	K (℃)	51.5	43.8	34.1	-
	α	1.05	0.63	0.45	-
Conductivity (kcal/m · hr · ℃)		2.3	2.3	2.3	2.5
Specific heat (kcal/kg · ℃)		0.25	0.25	0.25	0.18
Coeff. of convection currrent ($kcal/m^2 \cdot hr \cdot$ ℃)		9 (upper) 5 (side)	9 (upper) 5 (side)	9 (upper) 5 (side)	-
Compressive strength f_{28} (kgf/cm^2)		240	240	240	-
Elastic modulus E_{28} (kgf/cm^2)		2.3×10^5	2.3×10^5	2.3×10^5	3.0×10^5
Coeff. of thermal expansion (/℃)		1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}
Poisson's ratio		0.17	0.17	0.17	0.17
Placement temperature (℃)		20	20	20	-

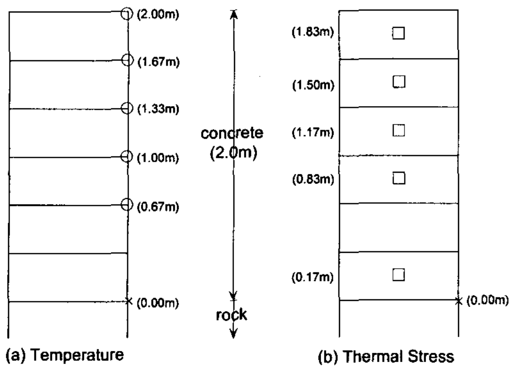

Fig. 1 Location of output

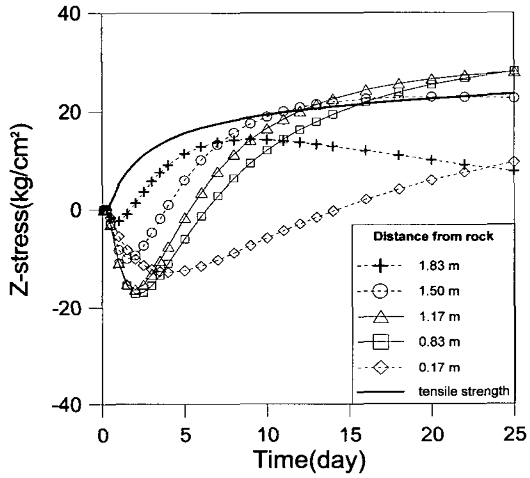

Fig. 2(a) Typical thermal stress vs. concrete age curve controlled by exterior restraints

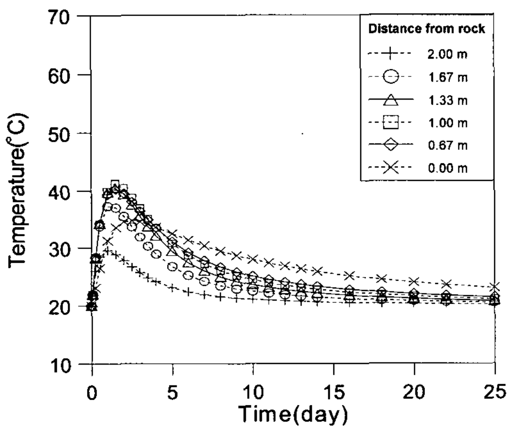

Fig. 2(b) Typical temperature rise vs. concrete age curve

The reason is that, if simply thinking, their increase will contribute to relieving the structural restraints in view of geometrical configuration. Therefore, parametric studies were carried out to investigate effects of wall sizes and lift heights on the thermal characteristics.

In this analysis, total 6 cases of wall lengths were employed, each increasing by 5m as shown in Table 4. Wall thickness of 50cm to 2m with increase of 50cm were applied. In terms of lift heights, in addition, 1, 2 and 3m were selected.

Finite elements for theoretical analysis were meshed by 0.5m in a direction of wall length. But meshes in a direction of lift height were employed differently in size such as 0.2m in case a lift height is 1m, 0.33m in both cases of 2.0m and 4.0m and 1.0m for bed rock. As for wall thickness, it was divided by 0.1m for both of 0.5m and 1.0m, 0.15m for 1.5m, and 0.2m for 2.0m. Results of analysis were recorded at nodal points for the case of temperatures and at elements for that of thermal stresses as shown in Fig. 1.

Figs. 2 (a) and (b) present typical results obtained by applying the prescribed modelling to the program.

3. Results of Analysis and Discussion

3.1 Evaluation Method of Crack Occurrence

According to Korean Concrete Specification, methods of estimating the possibility of thermal cracking in mass concrete can be classified into two. One is based on the previous working experience and the other is from thermal cracking index. The former may be applicable to a structure of less importance such as small size of retaining wall or the one to be free of problems from view point of past experiences.

Table 4 Parametric study

Cement type	Lift height	Wall length	Wall thickness	Remark
Type V B.F. slag cement Ternary blended cement	1.0m 2.0m 4.0m	5m	0.5m	
			1.0m	
			1.5m	
			2.0m	
		10m	0.5m	
			1.0m	
			1.5m	
			2.0m	
		15m	0.5m	
			1.0m	
			1.5m	
			2.0m	
		20m	0.5m	
			1.0m	
			1.5m	
			2.0m	
		25m	0.5m	
			1.0m	
			1.5m	
			2.0m	
		30m	0.5m	
			1.0m	
			1.5m	
			2.0m	

It is also regulated to be unnecessary to make an evaluation by means of thermal cracking index even for important structures such as reinforced concrete viaducts for railways or roadways, since lots of similar structures have been built or from the past construction records, harmful cracks have proved not to occur under the anticipated construction conditions. An alternative case not using thermal cracking index is when mock-up test was carried out. In this case, concrete samples are fabricated to a size that is expected to supply with results almost equivalent to actual structure. And then thermal stresses and temperature are measured in practice. For the measurement of thermal stress, in previous days strain gauges were used by favor of low price and the measured stains were transferred to thermal stresses by multiplying elastic modulus directly. But, thermal stresses calculated from strains are to accompany lots of errors as long as a relationship between temperature and elastic modulus is not confirmed, because elastic modulus is also dependent on the exothermic condition of concrete significantly. In practice, it is not easy to measure elastic modulus exactly in accordance with the increase of temperature. Currently, thus, thermal stresses are to be measured directly by embedding effective stress gauges inside concrete.

Most prevalent method will be to use thermal cracking index in evaluating the possibility of crack occurrence. In this case, temperature changes and thermal stresses are calculated considering all of factors such as materials used, construction method, environmental conditions and so on. Generally, thermal cracking index is expressed as a ratio of tensile strength of concrete to the stress as follows:

$$I_c = \frac{f_t}{\sigma_x}$$

where, σ_x refers to maximum thermal stress in tension to occur in the interior of member, and f_t refers to tensile strength of concrete at a time of calculating σ_x .

The larger the thermal cracking index, the less the possibility of crack occurrence. As the index becomes smaller, in other words, as the number of cracks increases and the crack width tends to grow. Standard values of the thermal cracking index are shown as follows:

- 1.5 and above : when cracks are to be prevented,
- 1.2 to 1.4 : when the width and the number of cracks are to be controlled while allowing cracking

- 0.7 to 1.1 : when not applicable to the above two.

Though increase of index values reduces the possibility of cracking, construction cost shall be increased correlatively as much as the possibility of cracking decreases. Therefore, it is necessary to establish the magnitude of cracking index effectively considering an expecting life of the structure and environmental conditions the structure is to be built.

3.2 Effects of Wall Thicknesses and Cement Types

Wall has a characteristics of crack occurrence mainly dominated by exterior restraints as mentioned earlier, but conditions of the restraint may be changed with an increase of wall thicknesses. The reason can be explained that, since it becomes more difficult for hydration heat to be emitted in the ambient air, both of interior and exterior restraints will work reciprocally and complicatedly. In order to investigate the relationship between wall thickness and crack occurrence, different thicknesses of 0.5m to 2.0m with increase of 0.5m were applied to theoretical calculation. Table 5 shows the results of maximum temperature rise and thermal cracking indices for various wall thicknesses and cement types under the condition that a lift height is fixed at 1m and wall length is at 5m. It can be observed from the table that thermal cracking indices in each cement kept almost constant irrespective of wall thicknesses and they were only different according to the types of cements as shown in Fig. 3. It indicates that the possibility of cracking is independent to wall thickness.

According to the results of analysis for a higher lift as shown in Fig. 4, however, the index was dependent significantly on the thickness of wall as a lift height is increased to 2m and 4m. The thicker the wall thickness, the significantly lower the index. It is generally known that thicker concrete

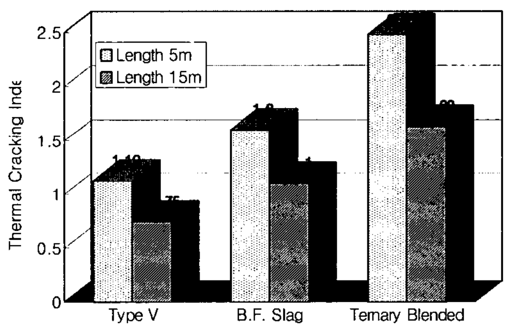

Fig. 3 Thermal cracking indices for different types of cements

Table 5 Results of thermal analysis for different types of cement (a Lift height 1m, Length 5m)

Cement	Thickness (m)	Max. temperature		Thermal cracking index		
		Magnitude(℃)	Occurrence(days)	Index	Occurrence(days)	Location
Type V	0.5	42.3	1	1.25	6	center
	1.0	47.5	1	1.12	10	〃
	1.5	48.9	1	1.12	15	〃
	2.0	49.9	2	1.14	15	〃
B.F. Slag Cement	0.5	33.9	1	1.89	7	center
	1.0	38.5	2	1.60	15	〃
	1.5	40.8	2	1.55	15	〃
	2.0	41.7	2	1.57	15	〃
Ternary Blended Cement	0.5	28.5	2	3.07	14	center
	1.0	32.3	2	2.48	16	〃
	1.5	33.7	2	2.32	16	〃
	2.0	34.3	2	2.33	17	〃

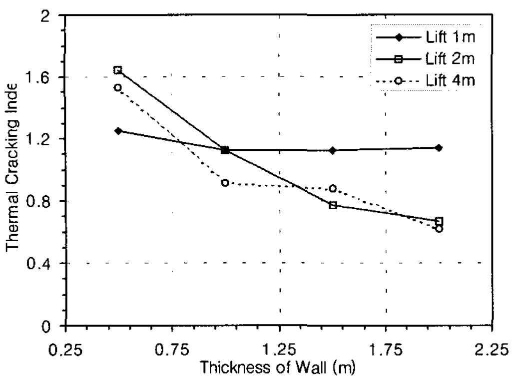

Fig. 4 Relationship between wall thickness and thermal cracking index (Length 5m, Type V cement)

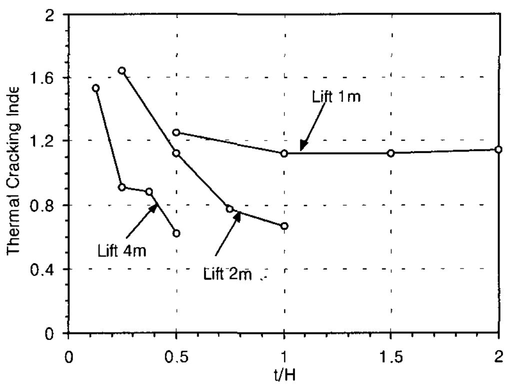

Fig. 5 Relationship between ratio of wall thickness to lift heights and thermal cracking index (Wall length 5m,Type V cement)

member has more possibility of cracking due to hard emission of hydration heat outside. But actual result appeared to be opposite to one expected. This may be explained as follows: too low ratio of thickness to height is mainly governed by exterior restraints which overwhelm the critical crack occurrence. Once the ratio arrives at a certain value, however, it can be helpful to release exterior restraints rather than harmful effect associated with hard emission of heat. Because of this, the possibility of cracking was decreased.

Fig. 5 shows the relationship between the ratio of wall thickness to lift height (t/H) and thermal cracking index. The purpose of this is for evaluating the degree of restraints for a lift height. It can be observed from this figure that thermal cracking index is significantly dependent on t/H as the magnitude of a lift height increases. Comparing a lift height of 2m with that of 4m, as an illustration, a lift height of 2m has larger thermal cracking index than that of 4m, because curve of 2m has stiffer slope with increase of t/H values. It can be inferred from this result that the possibility of crack occurrence shall be different according to the height of concrete placement even though all of wall sizes are same each other.

Considering the location of crack occurrence, a lift height of 1m is affected by exterior restraints due to low height of concrete placement in compare with thickness, so cracks start to develop at the center of member which may cause the problem of structural stability. With increase of heights of concrete placement, in the meanwhile, interior restraints become increased but exterior restraints are reduced comparatively. Thus, the location of cracking shifts to the surface of structure, which becomes much more stable structurally. However, too much increase of a lift height results in the increase of cracking again, because interior restraints work as a main factor of thermal crack development associated with rapid acceleration of internal temperature. It can be concluded that to place concrete up to a level of properly balancing exterior restraints with interior ones is the best way to minimize the possibility of crack occurrence. Therefore, it is most important to determine a lift height in a planning step through parametric study before placing concrete.

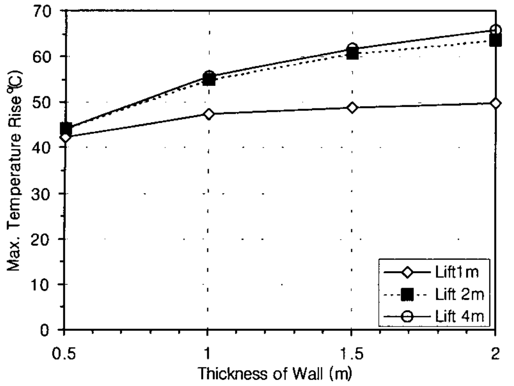

Fig. 6 Maximum temperature rise associated with different wall thicknesses (Type V cement)

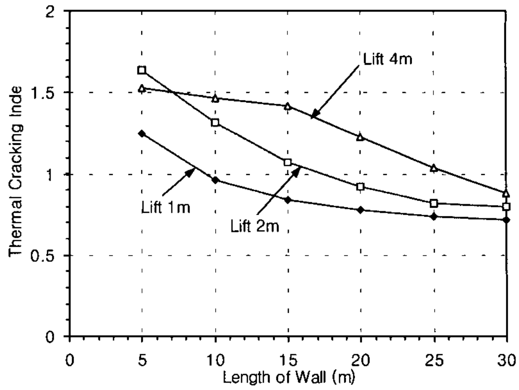

Fig. 7 Relationship between length of wall and thermal cracking index (Thickness=0.5m, Type V cement)

In view of effects of cement types on temperature rise, anti-sulphate cement showed the highest temperature under the same conditions of a lift height and wall length as shown in Table 5 and Fig. 6. The thicker the wall thickness, the lower the percentage of the total heat of hydration that will escape into ambient air, which means the internal temperature became higher. It is also found that shallower height of lifts resulted in the lower rate of temperature rise with increase of wall thickness. But it should be noted from the figure that maximum temperature did not increase proportionally as much as the rate of increase of lift heights.

3.3 Effects of Wall Length

Effects of wall lengths on thermal cracking were investigated through parametric study that varies lengths by increase of 5m. From Fig. 7 obtained using anti-sulphate cement, it is found that cracks occur more easily with increase of wall lengths under the condition of wall thickness being fixed. The possibility of crack occurrence associated with wall length was greatly affected by height of a lift. For example, 1m lift had a slight decrease of thermal cracking indices, but 4m lift appeared a rapid reduction of curvature after 15m of wall length. It can be found that lower height of lift has not always a beneficial effect on the prevention of cracking as discussed in the section 3.2, but optimized balance between interior and exterior restraints, which are directly related to the size of wall length and lift height, can decrease efficiently the possibility of cracking. The result may be due to that cracks were severely governed by exterior restraints when the ratio of wall length to lift height (L/H) is on the large side, but main factor of cracking moves slowly to interior restraints as L/H increases, namely when height of a lift is employed deeper.

Fig. 8 shows relationship between thermal cracking indices and ratio of wall length to lift height (L/H) which represents the degree of restraints for structural members. It can be observed that even normalized lengths, which refer to wall lengths divided by a lift height, had different values of cracking indices depending on a lift height. It represents that, though restraint conditions are same, i. e., for an identical concrete structure, the degree of restraints can be different according to heights of a lift. In other words, depending on the height of a lift, interior restraints may control the development of cracking or exterior restraint may do as mentioned earlier. Thus, in order to prevent or minimize the thermal cracking, it is necessary to carry out thermal analysis to determine the block size before placing concrete.

In a standpoint of temperature rise associated with wall length, when magnitudes of wall thicknesses and lift heights were constant, temperature rises were same irrespective of length of wall.

It can be also noted that, since in compare with a footing or a base of the structure the thickness of wall is comparatively shallow and also temperature rise was not much affected by the length of wall, the dependence of temperature on the lift height was not severe.

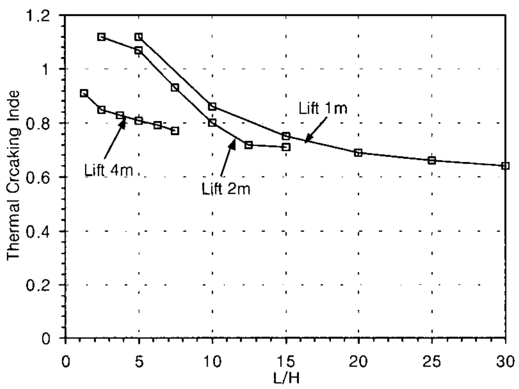

Fig. 8 Relationship between ratio of wall length to a lift height and thermal cracking index (Thickness=1m, Type V cement)

4. Conclusions

(1) Concrete which has higher thermal coefficients from adiabatic temperature rise test has more possibility of cracking as expected. Thus it is desirable to use the cement blended with mineral admixture to control thermal cracks in mass concrete.

(2) In wall structures such as retaining walls or side walls of a concrete caisson, application of too low lift heights may have a possibility of developing cracks which pass through section area at the center of a member, because the cracking is subjected to the control of exterior restraints. However, the increase of a lift heights becomes to reduce the effect of exterior restraints, while increases the degree of interior restraints. This result contributes efficiently to the control of crack occurrence.

(3) Height of a lift has a significant effect on cracking in compare with thickness and length of a wall. On the contrary of what is expected, therefore, to increase heights of a lift in mass concrete does not always do harmful to structural stability.

(4) Since same geometries in wall structure can have different effects on boundary restraints according to inner thermal conditions, it is recommended to carry out thermal analysis prior to concrete placement and to select an optimized lift height where internal and external restraints are to be balanced.

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