Thermal Stress Cracking Phenomena of Low-heat Hydration Concrete with Cement Ingredient Dependency

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ABSTRACT：

The thermal stress cracking phenomena of low-heat hydration concrete were observed at massive concrete casting site, and complex phenomena of stress and strain development with changing creep coefficient, changing modulus of elasticity, and their age dependency were investigated. Trial mixings and their physical tests of wide range ingredients of blended cement were performed in order to investigate relationships between ingredient of low-heat hydration cement and thermal stress crack characteristics. Sensitivity for cracking was investigated by analyzing tensile strength obtained by two methods, ordinary splitting test and direct pull-test. Tensile strength obtained by these tests were compared by taking ratio of those strength, since direct pull-test was estimated to be more sensitive to micro-failure of concrete and this ratio is used as an indicator of sensitivity for cracking. And relationship between sensitivity for cracking, and cement ingredient and its physical characteristics was investigated.

Based on these studies, two results were obtained. First, thermal stress at site cannot be simulated by a simple thermal stress analysis recommended by the Japan Society for Civil Engineering, since it dose not provide accurate enough physical model which should vary very much with age of setting, age-dependent modulus of elasticity, creep coefficient of those especially young age, and they are not usually taken into account accurately. Secondly, sensitivity for cracking and hydration shrinkage depends on cement ingredient (clinker, blast-furnace slag, fly ash, and their proportion), and fineness of especially blast-furnace slag. Taking these results into account, more accurate appreciation of thermal crack probability will be achieved.

1. Introduction

The characteristic of thermal stress crack depends on temperature variation, tensile strength of concrete, modulus of elasticity, creep coefficient, which depend on aging and hardening process of concrete. The probability of thermal stress crack is usually evaluated by thermal stress analysis, which takes into account all these characteristics. The analyzed thermal stress is compared to the tensile strength the ratio of which the probability of cracking is estimated. But because of the complexity of the phenomena, this analysis is not always successful.

The low-heat hydration concrete using low-heat hydration cement was applied at the massive concrete foundation of Akashi-Kaikyou Bridge, which is the world's largest suspension bridge (see Table.1, Table.2).

Table.1 specimen of low-heat hydration cement (example)

(1) physical characteristics

gravity	specific surface area	setting start	setting end
3.00	4.060 cm2 / g	270 minutes	407 minutes

(2) main chemical ingredients

ignition	calcium oxide	magnesium oxide	sulfur trioxide
1.4 %	48.7 %	4.2%	2.0%

(3)mix proportion of ingredients

Portland cement	fine blast-furnace slag	fly ash
30%	70%	0%

(4)heat of hydration

7 days	28 days	91 days
40.4 cal/g	46.5cal/g	50.6 cal/g

Table.2 mix proportion of low-heat hydration concrete and requested physical conditions

(1)Mixture proportion (example of 3P foundation)

W/C (%)	s/a (%)	unite quantity(kg/m^3)					Chemical admixture	
		water	cement	gypsum	sand	aggregate	SP9N	775S
53.5	41.0	140	260	30	710	1157	1.1%	2.5A

(2)Required physical conditions

design strength	slump	area(%)	bleeding	casting temp	adiabatic temp. rise
240kg/cm^2	8±2.5cm	4±1%	under 5%	20deg. centigrade	under 25 degrees

Real phenomena of concrete hydration process were monitored at the site such as temperature, strain, and stress, which were compared to laboratory simulation experiment to investigate and confirm the precise phenomena. At the initial stage of aging, compressive stress was found smaller than calculated or predicted due to the smaller modulus of elasticity and higher creep coefficient than estimated by mixing tests, and this makes concrete easier to crack than estimated. Hydration shrinkage was also measured, which produce additional tensile stress and makes concrete even easier to crack.

Table.3 blended cement for mixing tests

Producer	Specific surface area (cm^2/g)	Mixture proportion (%)			kind of clinker
		Clinker	Slag	blast-furnace	
A corp.	3330	25	75		moderate portland
B corp.	3240	75		25	low heat
C corp.	3900	40	30	30	low heat
D corp.	4500	70	30		low heat
E corp.	3110	25	75		moderate portland
F corp.	3880	35	45	20	moderate portland
G corp.	3910	25	55	20	moderate portland
H corp.	4420	30	50	20	low heat
I corp.	3400	20	60	20	moderate portland
2P foundation	4860	32	48	20	moderate portland
3P foundation	4850	30	70		low heat

(*)2P,3P are names of main tower foundations of Akashi-Kaikyou Bridge.

Wide range cement-ingredients of trial mixings were performed in order to investigate relationship between ingredient of low-heat hydration cement and thermal stress crack characteristics, such as age dependent coefficients, hydration temperature hysteresis, hydration shrinkage and sensitivity for cracking. Here, sensitivity for cracking was measured by applying ratio of tensile strengths obtained by ordinary splitting test and direct pull-test, since direct pull-test was considered to be more sensitive to inside failure of concrete, whose matrix of specimen is assumed to be evenly tensile.

Sensitivity for cracking is found dependent to cement ingredient. The smaller proportion of blast-furnace slag and/or ***alite*** and the less fineness of cement particles resulted in less sensitivity for cracking. Hydration shrinkage was also found dependent to cement ingredient, as the smaller percentage of blast-furnace slag and/or ***alite***, resulted in smaller hydration shrinkage.

2.Field measurement of thermal stress phenomena

The concrete applied at Akashi-Kaikyou Bridge foundation was a low-heat hydration concrete, whose maximal temperature rise induced by concrete hydration is 25 degrees. Measuring instrument for stress, strain, temperature were embedded inside two massive concrete foundations of suspension bridge (see Fig.1, Fig.2).

Narrow-width cracks were detected by measuring stress and strain inside the concrete layers, whose height was 1.5 meters in standard and were placed with the interval of approximately two weeks on top of previous layers (see Fig.3). Marrow-width cracks occurred at the early stage of the temperature descending, while measured strain was still compressive and measured tensile stress was small enough to avoid cracking.

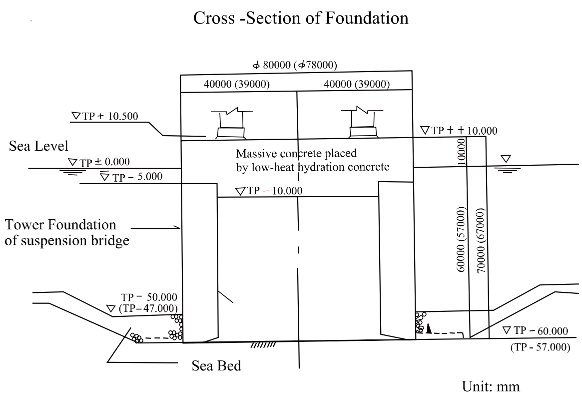


Figure.1 concrete foundation of Akashi-Kaikyou Bridge towers

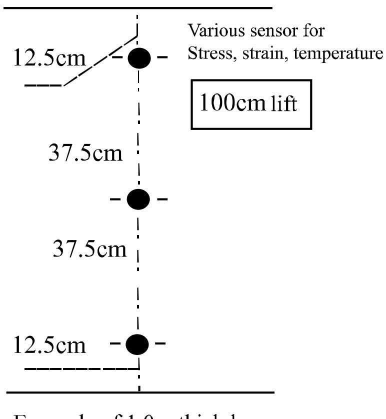


Figure.2 standard portion of measuring instruments inside the concrete layer

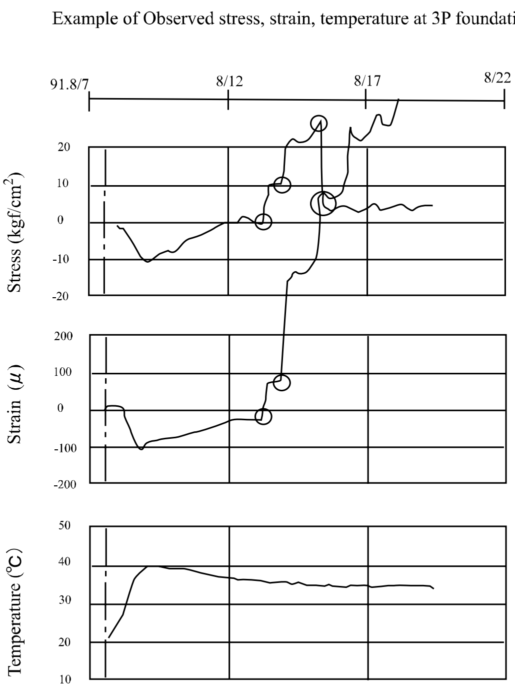


Figure.3 example of measurement ; stress strain and temperature

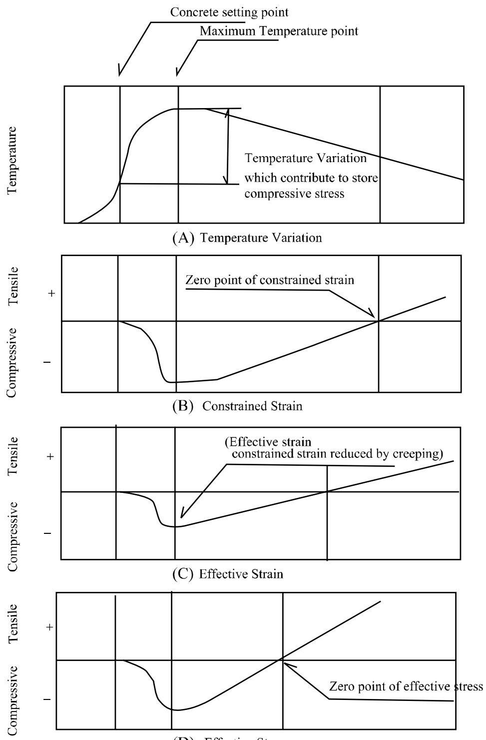


Figure.4 modeling of concrete hydration phenomena

The phenomena can be considered as follow (see Fig.4). Concrete stores compressive stress with ascending temperature, but only after concrete itself became hard enough and so as the modulus of elasticity. Creep coefficient is large at the early stage, and plastic deformation of concrete makes it seem to be even larger so that compressive stress does not store up as expected since concrete stress is usually calculated with physical properties obtained by trial mixing test at the age of 28 days.

To discuss about the strain inside restricted concrete, which contribute to produce actual stress, <effective strain> is defined as follow, Definition of Effective Strain

<effective strain> = <temperature variation>×<coefficient of linear expansion> — <measured real strain>

Effective strain is considered to decrease further with creeping and plastic deformation. And it decreases even further with concrete hydration and development of elastic modulus, since proceeding hydration holds compressive strain (effective strain) inside the microstructure of concrete matrix and effective strain superficially seems to decrease. Due to all these phenomena, even if measured strain was still compressive, concrete stress was tensile so that concrete cracks occurred.

To verify hydration shrinkage of low-heat concrete, stress-free strain gauge were embedded in the concrete, which enable to measure strain of non-stress concrete. Figure.5 shows an example how stress-free strain changes during hydration process or temperature ascending and descending. In the figure, stage.1 shows concrete hydration process from placed point to setting point, stage.2 shows process from setting point to maximum temperature point, and stage.3 shows process after maximum temperature point. A gradient of stage.1 is considered as a simple coefficient of linear expansion, but gradients of stage.2 and stage.3 vary from stage.1. Relationship between temperature and strain is linear in stage.1 and in stage.2, while superficial coefficient of linear expansion at stage.2 is smaller than stage.1, and that of stage.3 is larger. This means concrete expanded or shrunk linearly with temperature, but there is some other negative strain at stege.2 and stage.3, which is assumed to be a hydration shrinkage of over 100 x 10^{-6} in this case.

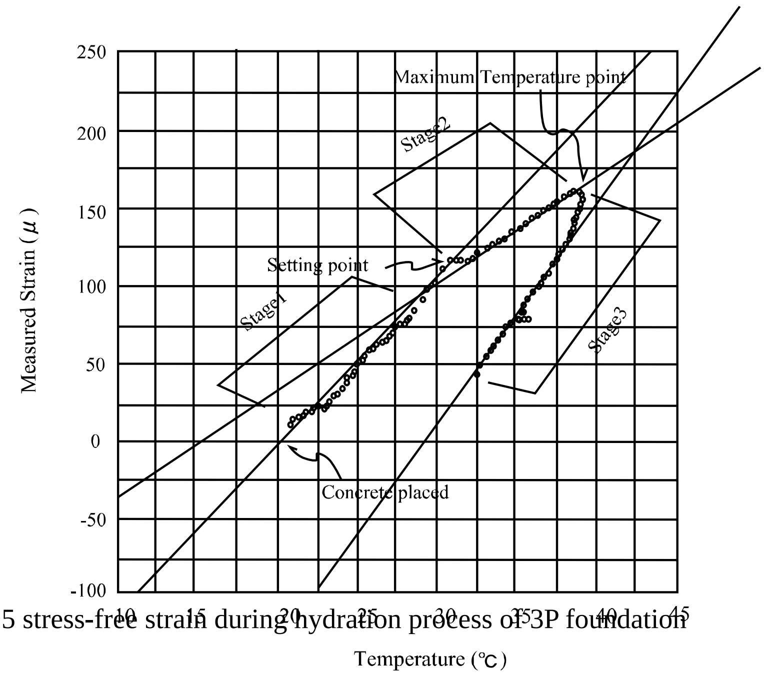


Figure.5 stress-free strain during hydration process of 3P foundation

3.Recreating thermal stress crack phenomena by laboratory experiment

In order to ascertain thermal stress crack phenomena of massive concrete observed at the site, laboratory examination was performed at University of Horishima by professor Tasawa. Based on the measured condition of concrete placed at the site, such as mix proportion, temperature hysteresis, restriction condition, concrete placed at the laboratory was observed. Two standard specimens were set in the curing box, in which temperature hysteresis was precisely recreated. One specimen was restricted as same as the concrete at the site, and other specimen was set without restriction, so that hydration shrinkage with the same temperature hysteresis were able to be observed.

These laboratory experiments recreated the thermal stress crack phenomena what we observed at the site. First, thermal stress crack occurred at the approximately same age (days after placing) although the strain was observed compressive which was exactly the same phenomenon at the site. Secondly, the specimen without any physical restriction showed shrinkage phenomenon, which was obtained by eliminating thermal strain. Fig.6 is the observed stress of both at the site and experiment. The phenomena observed are found reproducible and explainable as an assumed hydration phenomena.

Hydration shrinkage of around 100 x 10^{-6} was also observed by the definition shown below.

Definition of Observed Hydration Shrinkage

<hydration shrinkage>=<non-stress strain variation> — <temperature variation> × <coefficient of linear expansion>

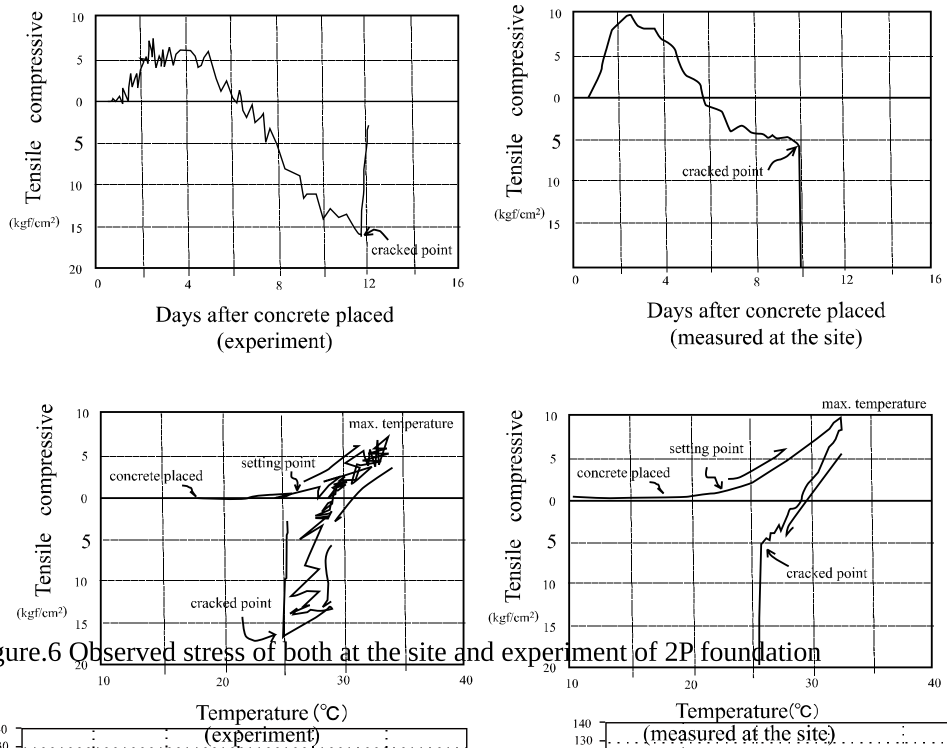


Figure.6 Observed stress of both at the site and experiment of 2P foundation

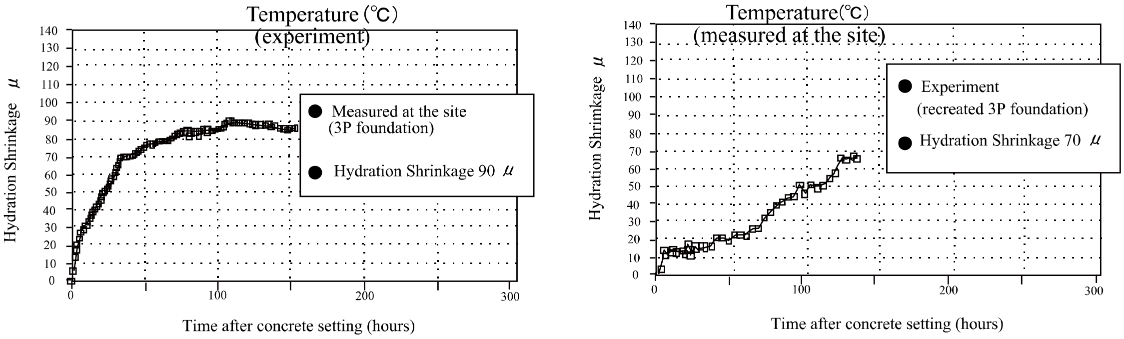


Figure.7 hydration shrinkage observed at the site and laboratory experiment (3P)

4.Mixing tests of low hydration concrete

In order to observe the influence of ingredient of low-heat hydration cement on physical coefficients, sensitivity for cracking, and hydration shrinkage, mixing tests of eleven ingredient cements were performed (see Table.3), here to keep the same physical conditions as the concrete placed at the bridge foundations, mix proportions varied with each low-heat hydration cement.

4.1.Tensile strength and sensitivity for cracking

Both splitting test and direct pull-test were performed to obtain the ratio of these test results (strength ratio), which was used as a parameter of sensitivity for cracking, since direct pull-test was considered to be more sensitive to inside failure of concrete, whose matrix of specimen is assumed to be evenly tensile. While tensile strength of splitting test is estimated only at the center cross-section of a specimen where in perpendicular direction stress is compressive and failure in cement could be reinforced by aggregate restriction. Here, it is possible to assume that the larger a strength ratio is, the larger sensitivity for cracking is. Standard specimen was loaded under a test device shown in Photo.1. Both end of the specimen were bonded to thick steel plate, which were pulled by hinged bearing so that specimen was loaded evenly without any bending moment.

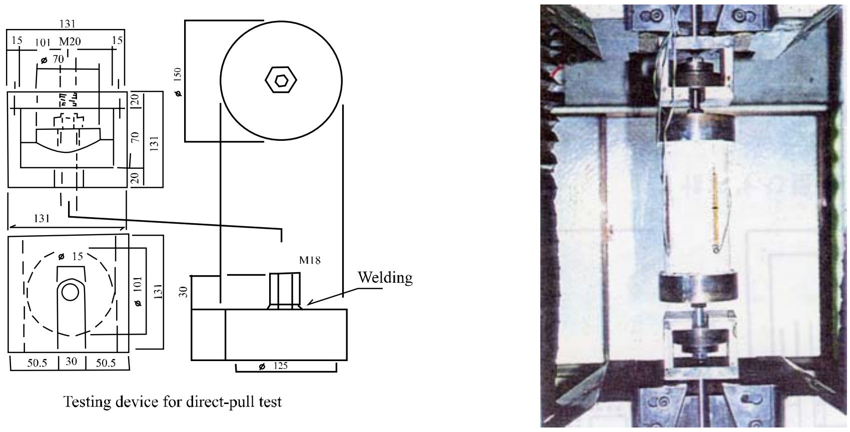


Photo.1 test device for direct pull-test

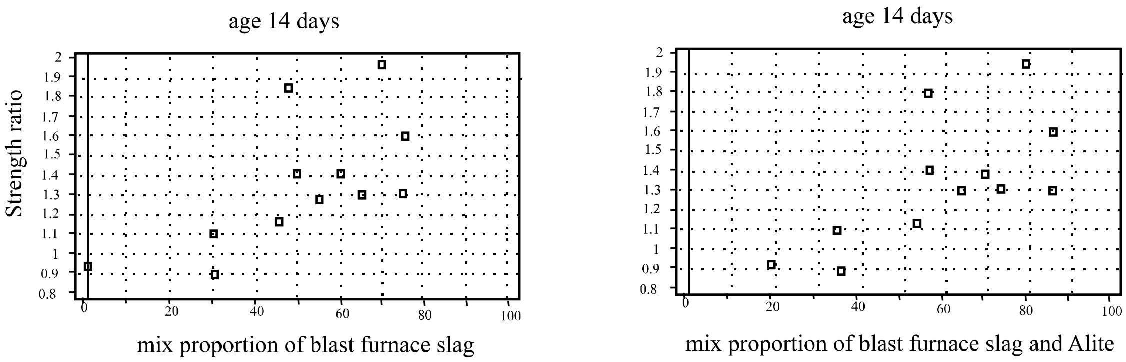
Table.4 explanatory valuables adopted for multiple regression analysis

objective valuable	explanatory valuables
sensitivity for cracking(*)	mix proportion of blast-furnace slag of blast-furnace slag and Alite of clinker fineness of cement of blast-furnace slag compressive strength of concrete

(*)which is obtained as a tensile strength ratio of ordinary splitting test ,and direct pull-test

Relationship between strength ratio and variation of cement ingredient was evaluated at several concrete ages by multiple regression analysis, and coefficients of multiple correlations were obtained. Here objective valuable was strength ratio, and explanatory valuable were the percentage of ingredients shown in Table.4, of which combinations of two valuables were adopted.

Figure.8 shows an example of relationship between strength ratio and percentage and fineness of each ingredient at the concrete age of 14 days, from which it is found that the concrete of low-heat hydration cement with higher percentage of slag and/or alite has a tendency to have higher strength ratio.



(※) Strength ratio : splitting test by direct pull-test

Figure.8 relationship between strength ratio and cement ingredient

The calculated coefficients of multiple correlations by multiple regression analysis are shown in Table.5. First of all, with growing age of concrete, coefficients of multiple correlations become smaller in any case of two explanatory valuables. Secondly, as already seen at Figure.8, in case percentage of slag is chosen as one of a explanatory valuable, coefficients of multiple correlations are relatively higher than other cases. And the combinations of explanatory valuables, as follow, have highest coefficients, which is significant enough to use their regression function to predict sensitivity for cracking at certain age of concrete. Especially, in case of slag percentage and its fineness, normalized coefficients of both valuables at the regression function are steady at all

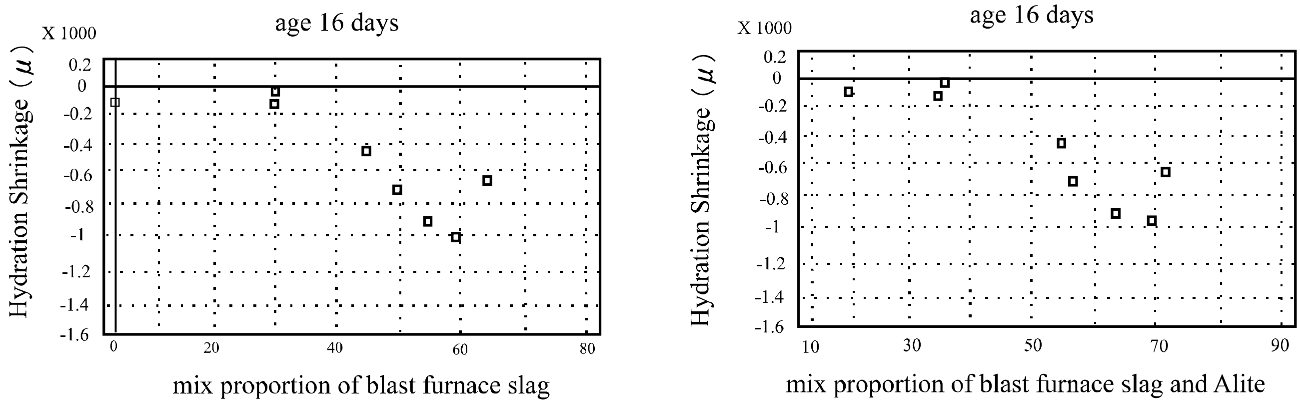
age (see Table.5).
○Essential combinations of explanatory valuables for sensitivity for cracking
1) slag percentage and slag fineness
2) (slag + alite) percentage and cement fineness
3) (slag + alite) percentage and slag fineness

Table.5 calculated coefficients of multiple correlations by multiple regression analysis

explanatory valuables		objective valuable (strength ratio)					
X1 (mix proportion)	X2 (fineness)	3days	7days	14days	28days	56days	91days
Slag+Alite	Cement	60.1	64.4	88.8	45.5	53.5	41.5
Slag+Alite	Slag	72.0	61.7	98.6	82.7	74.3	34.6
Slag+Alite	Cement	74.0	66.0	94.9	81.8	72.8	61.2
Slag	Cement	55.7	60.6	84.3	36.8	47.9	35.7
Slag	Slag	71.4	61.0	72.7	81.9	72.8	63.1
Slag	Cement	73.6	65.3	94.3	81.3	71.8	60.1

4.2.Hydration shrinkage

The same concrete and same cement was tested to obtain hydration shrinkage of several ages. At the age of two days, specimens were wrapped with vinyl chloride film to avoid drying out, and contact chips were set on the specimen body to measure hydration shrinkage. With these tests, unfortunately measurement of concrete shrinkage was failed so that we analyzed the shrinkage of cement only.



(※) Strength ratio : splitting test by direct pull-test

Figure.9 relationship between hydration shrinkage and cement ingredient

Figure.9 shows an example of relationship between hydration shrinkage and percentage and fineness of each ingredient at the concrete age of 14 days, and the same tendency found for sensitivity for cracking come to be evident, that the low-heat hydration cement with higher percentage of slag and/or alite, has a tendency to have higher strength ratio. But there was no evident tendency found for fineness.

Relationship between hydration shrinkage and variation of cement ingredient was evaluated at several ages by multiple regression analysis, and coefficients of multiple correlations were obtained. Here objective valuable was hydration shrinkage, and combinations of explanatory valuables were the same for the analysis of sensitivity for cracking (strength ratio). The calculated coefficients of multiple correlations by multiple regression analysis are shown in Table.6, which shows the combinations of explanatory valuables, as we have already seen for sensitivity for cracking, indicate its significance at all age of cement, except that the normalized coefficients of fineness of each ingredients are small enough to neglect for prediction of hydration shrinkage. Consequently, it is found hydration shrinkage of low-heat hydration cement simply depends on ingredients, especially slag and alite.

Table.6 calculated coefficients of multiple correlations by multiple regression analysis

explanatory valuables		objective valuable (strength ratio)			
X1 (mix proportion)	X2 (fineness)	9days	16days	30days	44days
Slag+Alite	Cement	① 86.7	② 89.1	③ 88.8	④ 89.4
Slag	Slag	⑤ 88.5	⑥ 90.1	⑦ 89.8	⑧ 89.2
Slag+Alite +Belite	Cement	⑨ 88.4	⑩ 91.0	⑪ 89.4	⑫ 89.4

4.3.Other physical coefficients

(1)Modulus of elasticity

Figure.10 shows results of modulus of elasticity, which indicates that tangent modulus of elasticity obtained by direct tensile pull-test is larger enough than gradient modulus of elasticity at 1/3 of compression strength ordinarily used for thermal stress analysis, so as to influence the calculated result of stress analysis.

(2)Creep coefficients

Figure.11 shows laboratory results of creep coefficients of the same concrete placed at the foundations site at the age of 40 hours, 3 days, and 7 days. The results indicate that the ordinary creep coefficients used for thermal stress analysis are significantly smaller than those of young age of low-heat hydration concrete.

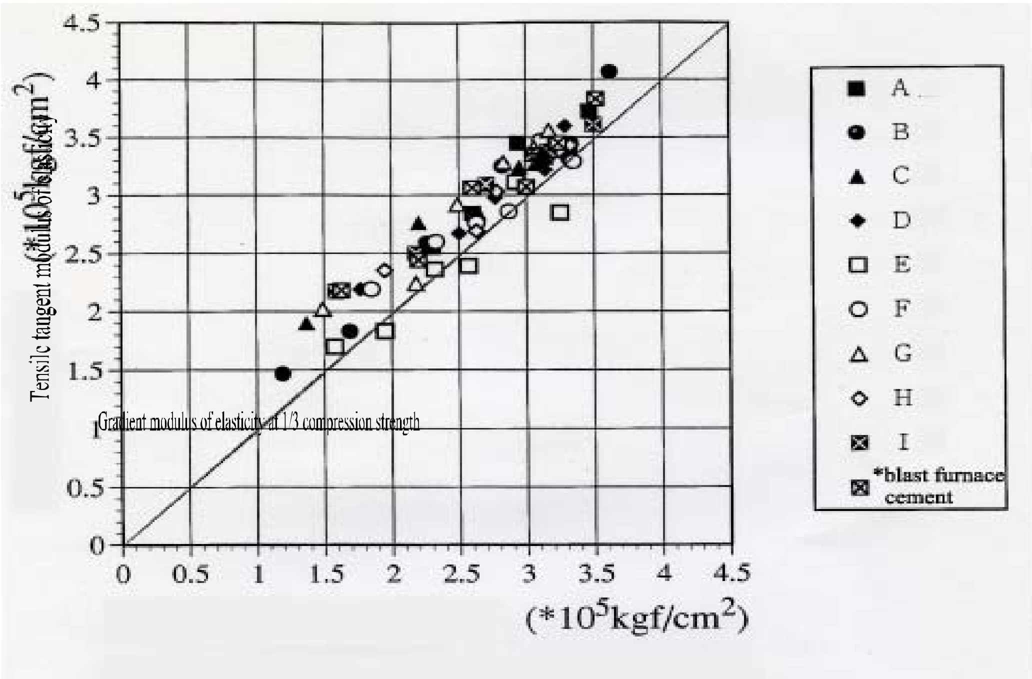


Figure.10 tensile tangent modulus of elasticity and gradient modulus of elasticity at 1/3 compression strength

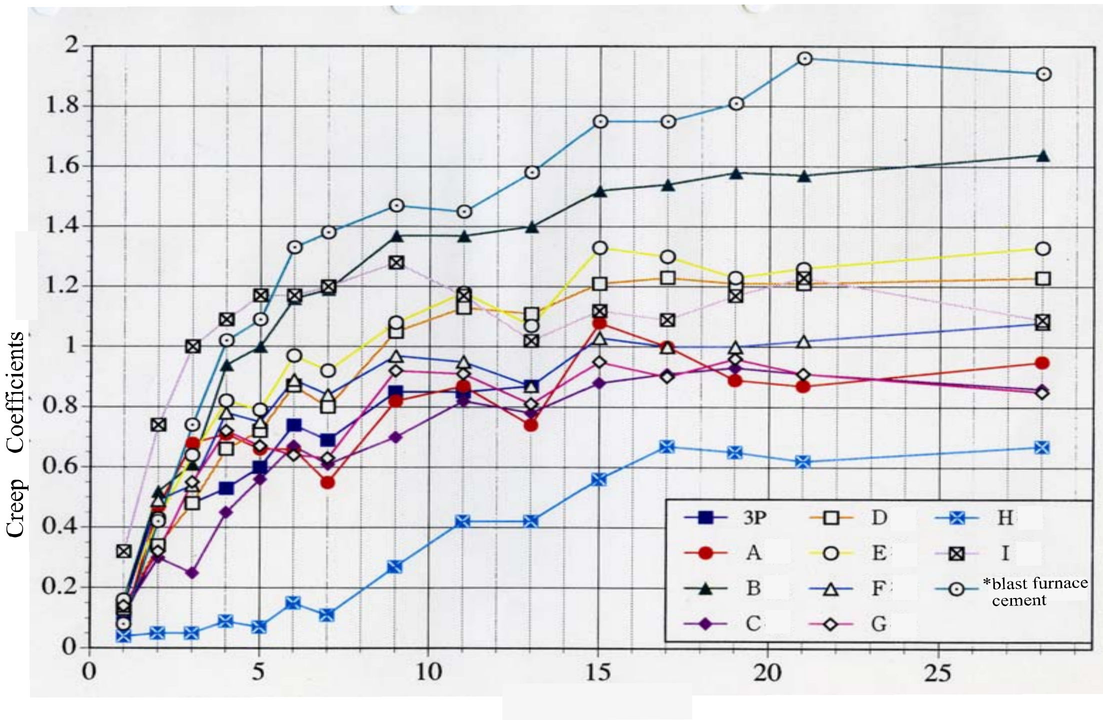


Figure.11 laboratory results of creep coefficients

5.Discussion

The cement and concrete adopted at the massive concrete foundations of Akashi-Kaikyou Bridge, whose maximum temperature rise was limited to 25 degrees, was considered not to cause any thermal stress crack based on the thermal stress analysis. Although it is found that both at the site and laboratory tests, the phenomena are more complicated than what we estimate by thermal stress analysis. The real compressive stress and strain of young age at the site is not exactly what it is measured, and it is found that they are smaller than estimated by analysis due to the larger creep coefficient and aging concrete which contains compressive strain inside concrete microstructure and makes effective compressive strain smaller for real stress. It is also evaluated that negative strain grows during concrete aging, and it is found as hydration shrinkage at laboratory experiment.

Modulus of elasticity used for thermal stress analysis is usually a gradient modulus of elasticity at 1/3 of compression strength. However tangent modulus of elasticity obtained by direct tensile pull-test is larger and apparently it is a proper valuable in case thermal crack occurs in a negative stress concrete.

And all of these coefficients applied for thermal stress analysis are usually obtained by mixing test of specimen cured at the temperature of 25 degrees centigrade, while these coefficients at the site are affected with the temperature hysteresis, which makes the results of the analysis even more inaccurate.

As shown before, sensitivity for cracking is able to estimate by strength ratio (ratio of tensile strengths obtained by ordinary splitting test and direct pull-test) and it depends on percentage and fineness of each ingredient, especially those combination of slag and alite as follow, so that the ingredients of blended cement have to be taken into account for thermal stress analysis to estimate probability for cracking. And it is found possible to model and apply strength ratio of a function of valuables below as a safety factor for thermal stress analysis, since calculated coefficient of multiple correlation for these valuable at young age is large enough to indicate possibility for modeling.

1) slag percentage and slag fineness
2) (slag + alite) percentage and cement fineness
3) (slag + alite) percentage and slag fineness

Hydration shrinkage of low-heat hydration cement simply depends on ingredients percentage, especially slag and alite at each age. It is also possible to model and apply this relationship as a shrinkage function of valuables below. Here it is found that fineness of each ingredient does not affect hydration shrinkage as much as sensitivity for cracking. It is also found that up to a certain percentage of these valuables they do not affect hydration shrinkage, which means less percentage of these valuable improve hydration shrinkage.

1) slag percentage
2) alite percentage
3) (slag + alite) percentage

6. Conclusion

For the thermal stress analysis to obtain thermal stress, it is recommended to recreate the phenomena precisely as measured at actual concrete placement site, especially at young age. Coefficients such as modulus of elasticity, creep coefficient, tensile strength also have to be precisely modeled at young age of concrete, and temperature hysteresis have to be taken into account, which apparently affect these coefficients. Percentage of ingredients of blended cement and their fineness, mainly slag and alite, affect sensitivity for cracking and hydration shrinkage. These characteristics have to be modeled for thermal stress analysis. Modeling of sensitivity for cracking and hydration shrinkage were tried but still many problems exist to make it consistent enough. In order to avoid thermal crack, best blend of ingredients and their fineness have to be selected such as less percentage of slag and/or alite and less fineness of these ingredients based on the required conditions from the thermal stress analysis. These results are evaluated for the low-heat hydration cement and concrete. And it is assumed that other kinds of cement and concrete commonly have the same characteristics, but this assumption still has to be proved.

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