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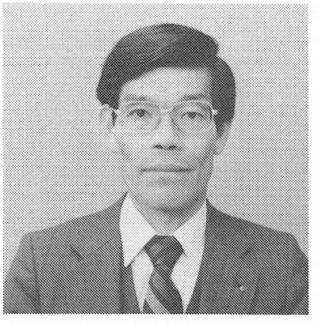
THE REDUCTION OF THERMAL STRESS CAUSED BY EXTERNAL RESTRAINTS WITH A SET-RETARDED CONCRETE

(Reprint from Transaction of JSCE, No.372, 1986)



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SYNOPSIS

In massive concrete structures thermal cracks are caused by external restraints in the vicinity of construction joints between old concrete and new one. This paper discusses the results of investigation performed to reduce such a thermal stress, by placing a layer of extraordinarily set-retarded concrete between them. Experimental study was carried out by changing the dosage of setting retarder for four long specimens. It is indicated from the study how to prevent such thermal cracks with the proposed construction method.

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1. INTRODUCTION

With the development of massive concrete structures in recent years, thermal cracks caused of such massive concrete has been a problem. These thermal cracks are caused by thermal stresses which are generated by volume change of concrete structure due to heat of hydration of cement under a certain restraint. The stresses consist of two categories, one is external restraint stress caused when volume change of new concrete is restrained by base rock or other abutting structure such as of old concrete and the other is internal restraint stress caused when the members are comparatively thick and volume change due to temperature difference between inner and outer surface is internally restrained.

A lot of studies on the analysis of such thermal stresses and reduction method has so far been carried out with some successful achievement. However, of these thermal stresses much has not been clarified yet on such items as material properties of massive concrete at the young age after being placed, causing condition of the thermal cracks, evaluation method of restraint and thus no reliable method for evaluation or reduction of these has been established.

Under such circumstances, the auther and his colleagues have previously presented the method of reduction of thermal stresses by placing a layer of set-retarded concrete admixed with setting retarder (The concrete is hereinafter abbriviated as SR-concrete) on construction joint between new concrete and existing structure for the reduction of external restraint stresses [1].

In this paper, the auther presents the results of his experimental study on such items as reduction mechanism of external restraint stresses, joint strength between new concrete and old one and method for determination of appropriate dosage of setting retarder. The content of this presentation is an extract from the study carried out after the previous one.

2. OUTLINE OF EXPERIMENT

(1) Materials and mix proportion

The cement used in the experiment was of normal portland, and while the coarse aggregate was river sand of the River Fuji (Maximum size = 25mm, Specific gravity = 2.60, Finess modulus = 6.56), the fine aggregate was that of Kashima (Specific gravity = 2.60, Finess modulus = 2.67) and the admixed agent was setting retarder of AE water reducing type of oxy-carboxylic acid salts. (It is of extraordinary set-retarding, but hereinafter simply abbriviated as setting retarder.) Mix proportion of concrete is as shown in Table 1.

(2) Method of mixing

In preparation of SR-concrete, it is well known that the time between hydration and admixture of setting retarder affects its set-retarding characteristics to a great extent [2]. In this experiment, mixing of SR-concrete was carried out in the following manner.

Table 1. Mix proportion

(1kg=9.8N)

Description	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit content (kg/m³)					
					W	C	S	G	AE water reducing agent	Extraordinary setting retarder
Ordinary concrete	8± 1	4 ±1	49.3	40.5	146	296	757	1114	0.592	0
SR-concrete	8± 1	4 ±1	49.3	40.5	146	296	757	1114	0.592	0 ~ 1.924
Mortar	13± 1	4 ±1	37.0	100.0	185	500	1700	0	1.0	0

At first, all the materials except setting retarder were thrown into a compulsory mixing plant and after 2 minutes of mixing they were left still for 8 minutes. Then after specified amount of setting retarder was added, all the materials were mixd for 1 minute.

As the setting retarder was of water reducing type, with its admixture of 0.1% to cement weight, the slump was increased about 1cm in comparison with that of about 8cm of base concrete while no substantial change of air before and after admixture was observed.

(3) Test of setting characteristics

To examine setting characteristics of SR-concrete used in the experiment, compressive strength test was carried out with a piece of 10$\phi\times$20cm. Curing of the test piece was performed in the room where temperature and humidity were controlled at 26.5℃± 1℃ and 85±5%RH respectively as the average curing temperature of the specimen to reach a maximum was estimated 26.5℃.

(4) Test specimens

Test specimens used in the experiment is of slender rectangular shape as shown in Fig.1. The upper part of new concrete is subject to external restraint caused by the bottom part of old concrete and four specimens in total were made with various dosage of setting retarder as shown in Table 2.

In the preparation of these specimens, immediately after placing of old concrete, setting retarder was spread on the construction joint to cause uneveners on the surface and the surface was treated with high pressure water after 15 hours. One month later after placing of old concrete, about 15mm thick mortar as shown in table 1 was laid thereon so as to effect better bonding to the old concrete. Then in order to reduce restraint of old concrete, SR-concrete with specified dosage of setting retarder was placed prior to the placing of new concrete. Thus new concrete, SR-concrete, and old one were integrated by compaction using vibrating machine.

To create similar condition to actual massive concrete structure in both temperature and curing, new concrete was covered around with wall of vinyl film and adiabatic material and heated with electric wire fixed on the side of specimen. Further, to permit free volume change of new concrete, when new concrete was placed, panels of thin plywood were inserted between forms, adiabatic material and respective specimens and at the time when concrete was set solid enough to stand by itself (about 4 to 5 hours after being placed) they were pulled out. Thus the specimens were made free from the surrounding restrictions.

Table 2. Content of specimens

Specimen No.	Dosage of setting retarder (C×%)
A 0	0
A 1	0.4
A 2	0.5
A 3	0.6 5

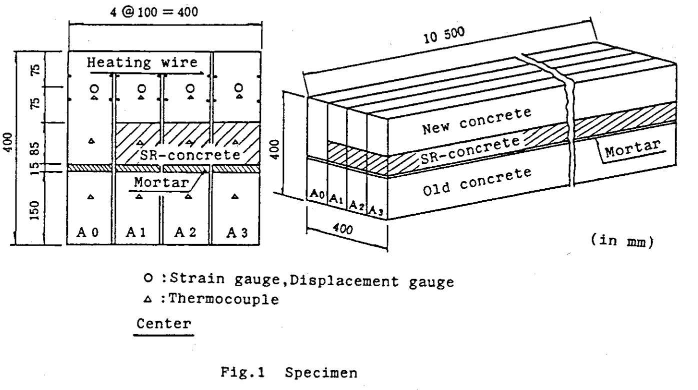

Fig.1 Specimen

(5) Dosage of setting retarder and thickness of SR-concrete layer

New concrete expands after being placed until it reaches its maximum temperature and then turns into shrinking stage. For this reason, to reduce restraint of old concrete, SR-concrete has to have enough deforming capacity even when new concrete is in shrinking process. According to the study results [3], limit value of enough deforming capacity of the concrete is less than about 0.8kgf/cm2 in its compressive strength. (At this stage the concrete can still be fluidified by means of vibrating machine.)

While the specimens in the experiment are modeled after wall type massive concrete structure of about 1.5m thickness, according to the results of previous experiment and measurement at site, of such a structures, maximum temperature of both new concrete and SR-concrete occurs at the age of 1.5 days and thermal change thereof after being placed is about 20℃ and 15℃ respectively. In this experiment, with control of much thermal change by adjustable heating with electric wire, the anticipated thermal transition at initial stage was substantially given to the specimens as shown in Fig.6. The heating pattern was nearly same as that of No.1-No.3 in Fig.6.

As above-described, in the case of wall type concrete structure having 1.5m thickness, the temperature reaches a maximum at the age of about 1.5 days. Therefor, so as to cover this target age of 1.5 days in dosage determination of setting retarder, the experiment was carried out at the respective ages of 1 day , 1.5 days and 3 days and the determination was made on the basis of previous test results of set-retarding characteristics so that the concrete had about 0.75kgf/cm2 compressive strength at these target ages. The results are shown in Table 2 and dosage of setting retarder to cement is shown in percentage by weight.

As SR-concrete layer as thick as about 10cm was found suitable for the experiment in consideration of the previous study [1], such thickness of 10cm inclusive of morter was adopted for the specimens.

(6) Items and method of measuring

As shown in Fig.1, temperature and strain were measured at the center of the specimens. Measuring gauges were thermocouple and buried-in type strain gauge (Electric resistance type strain gauge, apparent elastic modulus = 400kgf/cm2, L = 100mm). Further, at three crossections on one side of respective specimens,

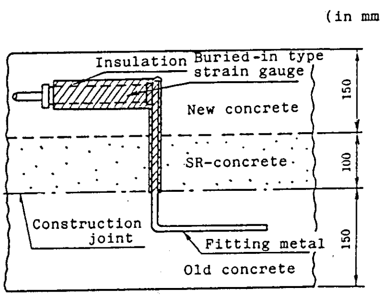

Fig.2 Setting of displacement gauge

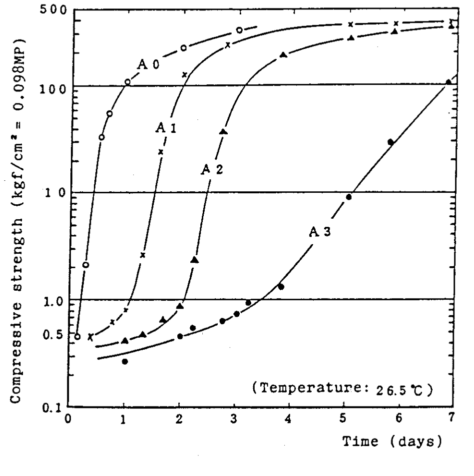

Fig.3 Compressive strength by elasped time

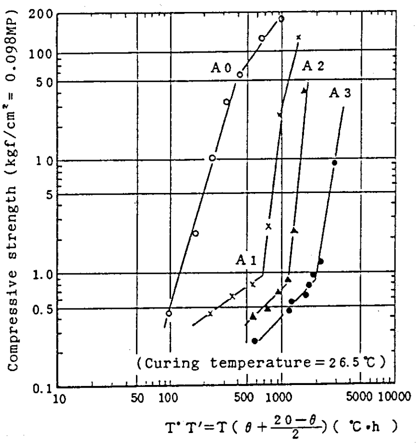

Fig.4 Relation between cumulative temperature and compressive strength

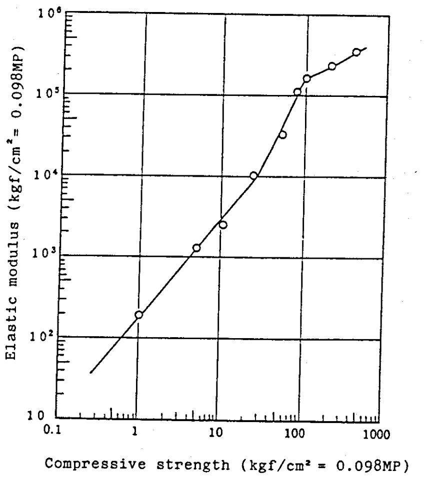

Fig.5 Relation between compressive strength and elastic modulus

relative displacement between new concrete and old one was measured by displacement gauge (precision ≒ 10^{-3} mm) utilizing the buried-in type strain gauge as shown in Fig.2. These measuring were carried out as long as three weeks immediately after new concrete was placed to the time when temperature stabilized.

In the analysis of these data, after thermal adjustment was made and initial value was set suitably, real values were obtained basing on the previous study results by the auther [4].

3. RESULTS OF EXPERIMENT AND CONSIDERATION

(1) Setting characteristics of SR-concrete

Experimental results of setting characteristics of SR-concrete are shown in Fig.3 and 4. Cumulative temperature in Fig.4 was calculated in accordance with the following equation oftained by the auther on SR-concrete [5].

Cumulative temperature $$T^{\circ}T'=T\left(\theta+\frac{20-\theta}{2}\right) \qquad (1)$$

Where, T: elasped time after hydration (h)
$^{\circ}T'$: assumed curing temperature of SR-concrete (℃)
θ: average curing temperature (℃)

According to the above equation, cumulative temperature of SR-concrete at a maximum temperature of new concrete is obtainable from the thermal transition of respective specimens as later described. (Shown in Fig.6) Compressive strength of the respective specimens obtainable from Fig.4 and elastic modulus thereof obtainable from study results for the same mix proportion as shown in Fig.5 [6] are put together in Table 3 with the said cumulative temperature.

(2) Temperature of concrete

Transition of temperature by elasped time of A1 specimen is shown in Fig.6. The new concrete reaches its maximum temperature at the age of 1.5 days when thermal change after being placed is about 20℃ while those of SR-concrete and old concrete are lower about 1.5℃ and 5℃ respectively. The temperature of concrete stabilizes within about 2 weeks.

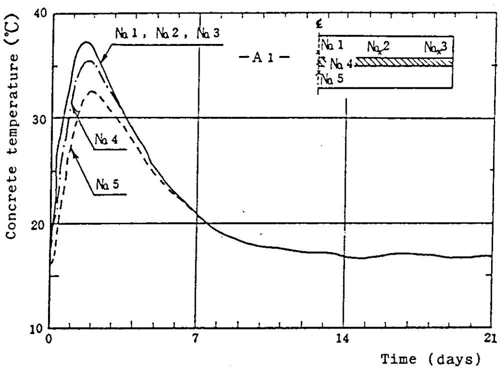

Fig.6 Concrete temperature by elasped time

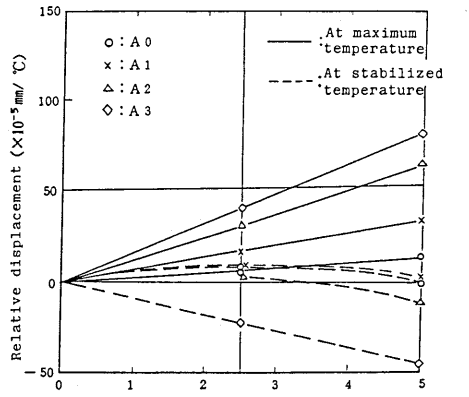

Fig.8 Relation between distance from center of specimen and relative displacement

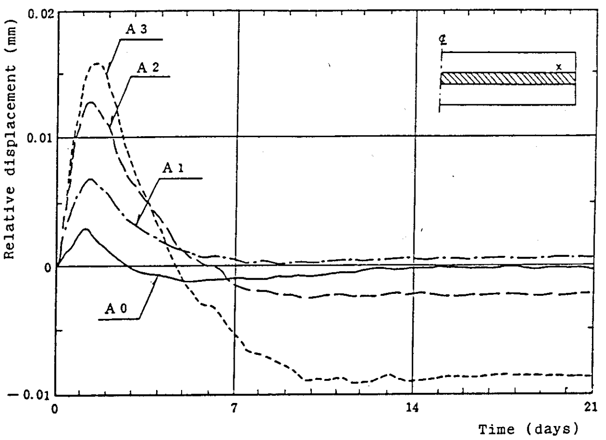

Fig.7 Relative displacement by elasped time

Table 3. Material properties of SR-concrete at maximum temperature of new concrete

(1kgf/cm² = 0.098MP)

Specimen	Cumulative temperature TT(℃·h)	Compressive strength σc(kgf/cm²)	Elastic modulus Ec(kgf/cm²)
A 0	900	150	200,000
A 1	870	9.0	2,500
A 2	850	0.6	90
A 3	800	0.3	40

Such an inclination is found nearly same among the respective specimens by means of adjustable hearting with electric wire and thus the initially anticipated thermal transition of about 1.5m thick massive concrete wall is almost reproduced.

(3) Relative displacement

Examples of relative displacement between new concrete and old one at construction joint are shown in Fig.7. Variance of the relative displacement among the respective specimens is found to a great extent despite of their nearly same thermal change as afore-mentioned. Further, with increased dosage of setting retarder and thereby delaied setting speed of the specimen, increased degree of relative displacement is observed. Moreover, in the case of A3 specimen of increased dosage, new concrete, which expanded at its maximum temperature, turned into shrinking as temperature stabilized and finally it became shorter than the old one because of such shrinkage. Despite that this inclination has been confirmed by the site experiment carried out on another occasion, the reason therefor has not been clarified yet pending further investigation. Comparing displacement in Fig.7 with caused stress in Fig.19 which later to be referred, it is found that the degree of relative displacement has a meaningful relation to the stress caused.

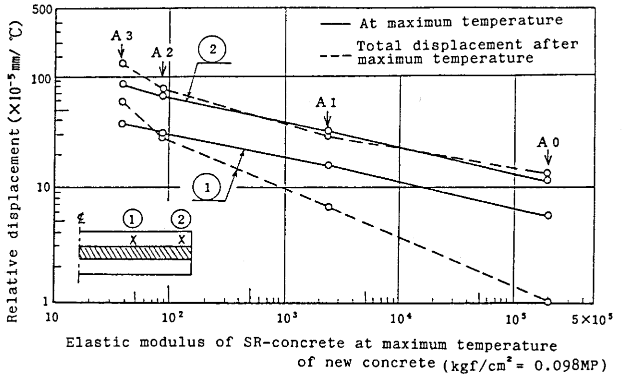

FIg.9 Relation between elastic modulus of SR-concrete at maximum temperature of new concrete and relative displacement

The relation between distance from the center of specimen and degree of relative displacement is as shown in Fig.8. The inclination is found of all specimens that relative displacement increases in proportion to distance from the center of specimen approximately.

The relation between elastic modulus of SR-concrete and relative displacement at a maximum temperature of new concrete is shown in Fig.9. They are in almost linear relation in logarithmic scale and this relation remains entiraly same even if elastic modulus is replaced by compressive strength.

Thus, it is conceivable that thermal stress can be reduced with relieving of restraint between new concrete and old one, resultant from such comparatively big displacement caused by casting of SR-concrete on construction joint.

(4) Restraint

While change of apparent strain by elasped time is shown in Fig.10, the relation between apparent strain and thermal change is as shown in Fig.11. Further, change of apparent strain of nonrestraint specimen is shown in Fig.11. Generally, restraint is shown in the following equation [9].

$$\text{Restraint } R=\frac{\alpha_f-\alpha_r}{\alpha_f} \qquad (2)$$

Where, α_f :strain change ratio of nonrestraint specimen (°C^{-1})
α_r :apparent strain change ratio of respective specimens (°C^{-1})

Using "α" obtained in Fig.11, the relation between calculated restraint by equation (2) and setting retarder dosage is shown in Fig.12. As shown in this Fig.12, as dosage of setting retarder increases, restraint rapidly decreases. Such an inclination is observed entirely same in the results of experiment previously carried out by the auther [1]. Further, restraint is somewhat bigger in uprising temperature than in dropping and this is conceivably due to still small elastic modulus of new concrete when temperature rises. The inclination coincides with the experimental results carried out by Mr. Aokage and his colleagues [7].

In order to investigate the effectiveness of setting speed of SR-concrete, the relation between compressive strength of SR-concrete at a maximum temperature of new concrete and restraint reduction ratio obtained by the following equation is shown in Fig.13.

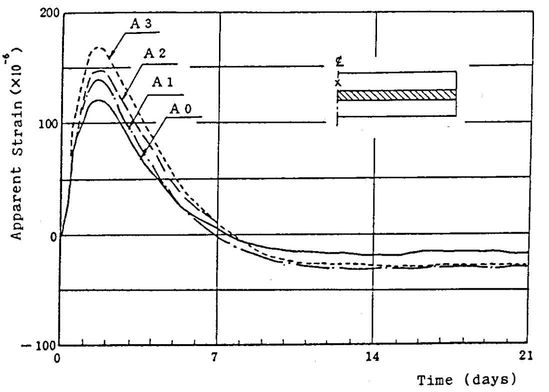

Fig.10 Apparent strain by elasped time

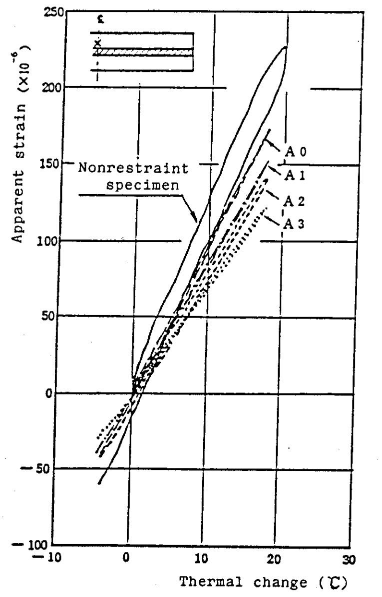

Fig.11 Relation between thermal change and apparent strain

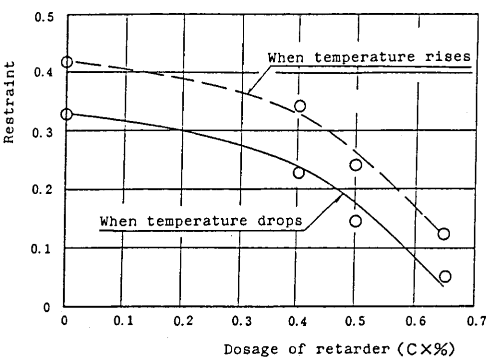

Fig.12 Relation between dosage of setting retarder and restaint

Restraint reduction ratio $K=\frac{R_{A0}-R_{Ai}}{R_{A0}}\times 100$ (%) ----------------------- (3)

Where, R_{A0} :restraint of conventional construction method (Specimen A0)
R_{Ai} :restraint of respective specimens (Specimen Ai)

It is found in Fig.13 that restraint reduction ratio rapidly increases as compressive strength of SR-concrete decreases. Also, it is seen in Fig.13 that in order to reduce restraint by half, setting of compressive strength of SR-concrete at about 0.7kgf/cm^2 is simply required.

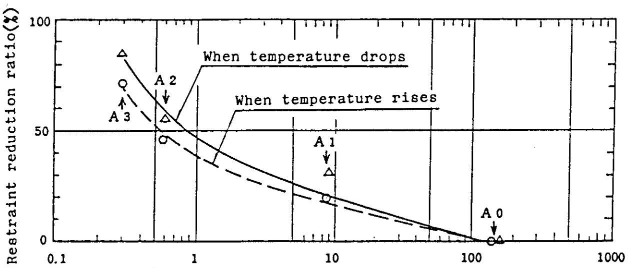

Fig.13 Relation between compressive strength of SR-concrete at maximum temperature of new concrete and restraint reduction ratio

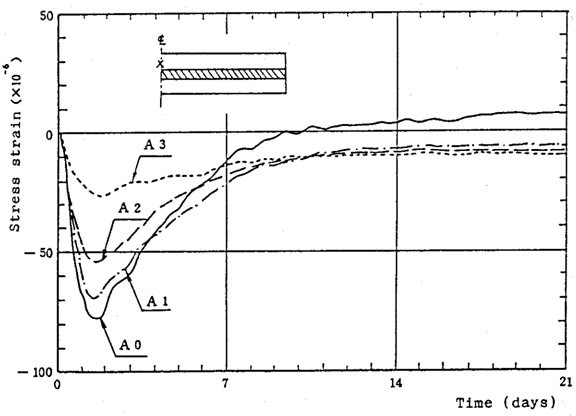

Fig.14 Stress strain by elasped time

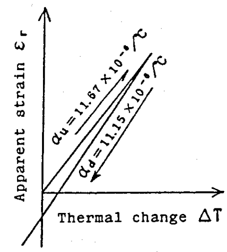

Fig.15 Model of free expansion and contraction of nonrestrained specimen

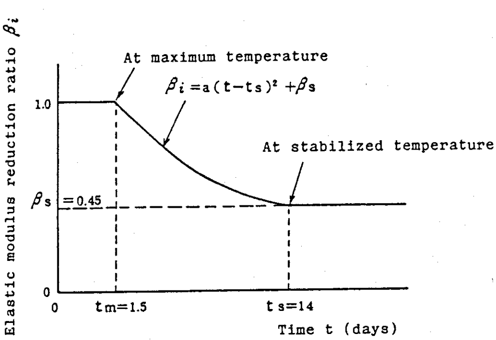

Fig.16 Reduction ratio of elastic modulus

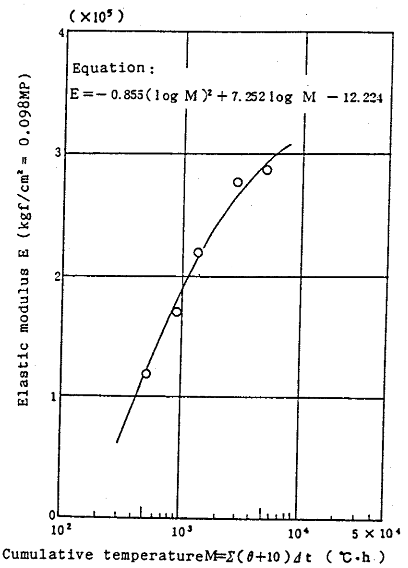

Fig.17 Relation between cumulative temperature and elastic modulus

(5) Stress caused

Stress strain involved in caused stress of new concrete is calculated by the following equation and the results are shown in Fig.14.

$$\text{Stress strain} \quad \varepsilon_s = \text{Effective stress strain}(\varepsilon_e) + \text{Creep strain}(\varepsilon_c) = \varepsilon_r - \alpha \cdot \Delta T \qquad (4)$$

Where, ε_r :apparent strain of respective specimens
α:strain change ratio of nonrestraint specimen (°C^{-1})
ΔT:thermal change (°C)

Strain change ratio of nonrestraint specimen is modeled as shown in Fig.15 with reference to Fig.11.

While elastic modulus reduction ratio ($(1+\phi)^{-1}$, ϕ:creep coefficient) is modeled as shown in Fig.16 basing on the experimental results of wall type structure by Mr. Aokage and his colleagues [7] as well as by the auther [11][12], elastic modulus is obtainable from cumulative temperature of respective specimens on the basis of the results of experiment carried out by the auther as shown in Fig.17 [6]. And stress caused of new concrete is calculated by the following equation with reference to that (4) of stress strain. (See Fig.18)

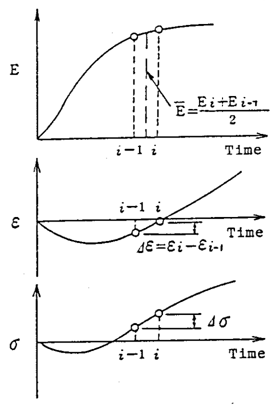

Fig.18 Stress calculation

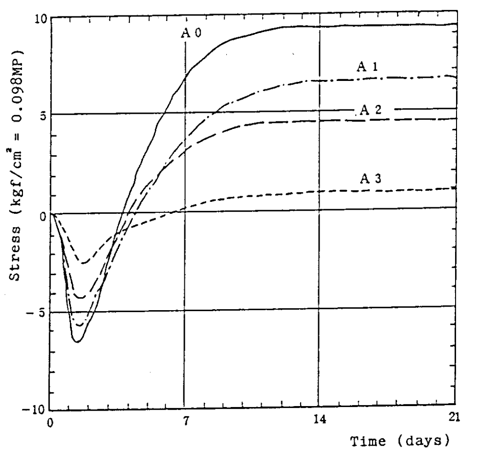

Fig.19 Stress by elasped time

$$\sigma_i=\sigma_{i-1}+\beta_i\times\frac{E_i+E_{i-1}}{2}\times(\varepsilon_i-\varepsilon_{i-1}) \quad \text{------------------------} \quad (5)$$

Where, σ_i:stress of concrete
E_i:elastic modulus of concrete at i step
ε_i:stress strain of concrete at i step
β_i:elastic modulus reduction ratio of concrete at i step

Calculated results by the above equation are shown in Fig.19. According to Fig.19, in the specimen of slower setting speed, the less compressive and tensile stress is observed and thus thermal stress is found much reduced by the application of this construction method.

Further, it is conceived that the relation of elastic modulus and compressive strength of SR-concrete at a maximum temperature of new concrete with stress reduction ratio obtained by the following equation is as shown in Fig.20 and 21, respectively.

$$\text{Stress reduction ratio } K'=\frac{\sigma_{A0}-\sigma_{Ai}}{\sigma_{A0}}\times 100\ (\%) \quad \text{------------------------} \quad (6)$$

Where, σ_{A0}:maximum compressive (tensile) stress in conventional construction method (Specimen A0)
σ_{Ai}:maximum compressive (tensile) stress of respective specimens (Specimen Ai)

According to the referred two figures (Fig.20 and 21), it is seen that similarly to the afore-mentioned case of restraint reduction ratio, stress reduction ratio has close relation to elastic modulus and compressive strength of SR-concrete and as these decrease, stress reduction ratio increases rapidly. Further, the reduction effect is found more notable in case of tensile stress than in that of compressive stress. This inclination is entirely same as in the case of restraint reduction ratio previously described.

(6) Joint strength

As afore-mentioned, in this method, comparatively big relative displacement between new concrete and old one is caused by placing of SR-concrete and this fact has been proven effective in the reduction of thermal stress. However, at the same time, it has to be concerned about that joint strength might be reduced by such relative displacement or increased bleeding of SR-concrete itself.

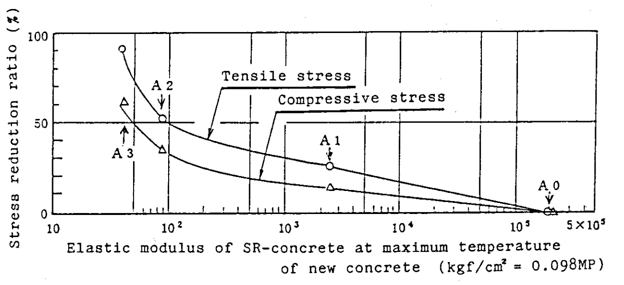

Fig.20 Relation between elastic modulus of SR-concrete at maximum temperature of new concrete and stress reduction ratio

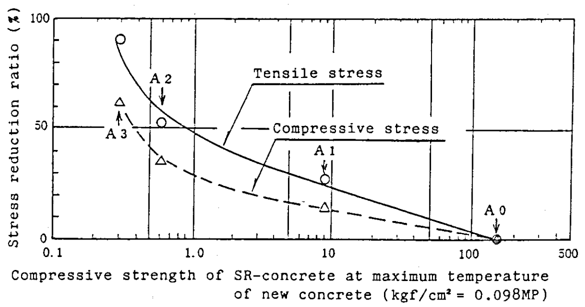

Fig.21 Relation between compressive strength of SR-concrete at maximum temperature of new concrete and stress reduction ratio

To investigate this joint strength problem, after vertical core-boring of 75mm diameter of respective specimens, flexural strength test of thus obtained pieces was carried out. The results are shown in Fig.22.

In Fig.22, the relative ratio between flexural strength of the respective specimens and that of concrete having no joint is shown and the inclination that joint strength reduces as distance from the center of respective specimens increases is observed. It is conceivable that such a phenomena is, as afore-discribed, due to the increase of relative displacement accompanied with increased distance from the center of the specimens. In this regard, in either case of conventional or proposed method, length limitation of construction joint is conceivably inevitable for securing enough joint strength required in actual construction.

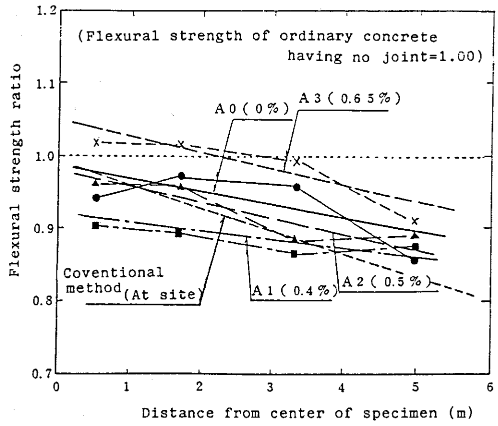

Fig.22 Distribution of joint strength with various dosage of setting retarder

Further, in Fig.22, it is seen that in this method, when dosage of setting retarder is in small quantity, joint strength happens to be somewhat less but not too much lower as compared with the case of conventional method. Also, in comparison with that in actual construction carried out by the auther, which is shown in Fig.22 with a broken line, the joint strength is in the range of almost satisfactory value. (Actual construction example : Gravity type retaining wall where following green cutting with high pressure water, mortar was laid and new concrete was placed thereon afterwards.)

In the case of increased dosage of setting retarder, flexural strength ratio of the specimen happens to be more than 1. It is conceived this is chiefly due to strength increase of SR-concrete itself. (In the experimental results, increased strength of SR-concrete used for A3 is 1.2 times as much as that of A0.)

(7) Reduction ratio of thermal stress and target of compressive strength

While the specimens used in the experiment are of rather small scale in comparison with actual structure and accordingly some limitation may exist for actual application, necessary dosage of setting retarder to attain target stress reduction when external restraint stress has to be reduced by this method was further investigated basing on the previous results. Target compressive strength of SR-concrete at a maximum temperature of new concrete necessary to attain the specified reduction ratio is obtainable from the ratio to tensile stress in Fig.13 and Fig.21 and it is as shown in Table 4. According to Table 4, for example, in the case of structure sustaining external restraint, setting speed has to be adjust with retarder so that compressive strength of SR-concrete becomes about 0.85kgf/cm^2 at a maximum temperature of new concrete in order to halve the caused stress using this proposed method.

Flow chart of dosage determination when this method is applied for avoidance of thermal cracks which are likely to be caused in massive concrete structure by external restraint, is recommended as shown in Fig.23. In the case when occurence of thermal cracks is feared probable in the application of conventional method after analysis thereof is made, it is advisable to take the following steps. At first, target reduction ratio to avoid cracks is set. Next, basing on the said target reduction ratio, target compressive strength of SR-concrete at a maximum temperature of new concrete is obtained from Table 4. Then, with estimation of thermal transition of new concrete upto the time of its maximum temperature referring to the results of thermal analysis of the object structure as well as those of previous experiments, dosage of setting retarder is determined so that compressive strength of SR-concrete conforms to the target under such thermal transition.

Thermal stresses caused in massive concrete structure represent, as well known, different features depending on various factors such as sectional area ratio and rigidity ratio between new concrete and old one, mix proportion, thermal transition and other relating matters.

Table 4. Reduction ratio and target compressive strength

(1kgf/cm^2 =0.098MP)

Reduction ratio (%)	Estimated compressive strength (kgf/cm^2) (1) Value by restraint reduction ratio	(2) Value by stress reduction ratio	$\frac{(1)+(2)}{2}$ (kgf/cm^2)	Target compressive strength (kgf/cm^2)
0.1	34	50	42	40
0.2	10	15	13	10
0.3	3.9	4.5	4.2	4.5
0.4	1.7	1.7	1.7	1.5
0.5	0.88	0.85	0.87	0.85
0.6	0.56	0.50	0.53	0.50
0.7	0.40	0.38	0.39	0.40
0.8	0.32	0.31	0.32	0.30
0.9	0.27	0.27	0.27	0.25
1.0	0.21	0.24	0.23	0.20

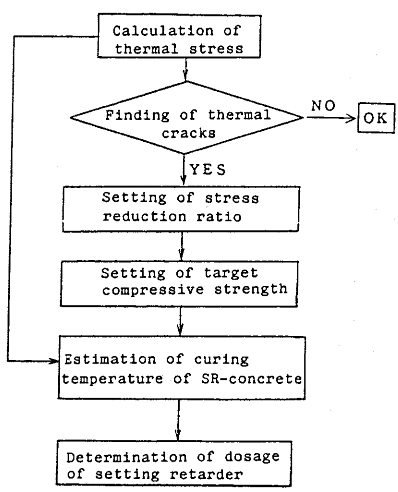

Fig.23 Flow chart for dosage determination of setting retarder

As afore-mentioned, the applicability of this method to actual construction may be limited to some extent because these study results were obtained from the experiment with rather small scale specimens and moreover, under the limited conditions of mix proportion and thermal transition. However, despite of such limitations, the auther would like to propose the results of this study as an useful guidline for the reduction of external restraint stress with a layer of SR-concrete.

4. CONCLUSION

As the results of experimental investigation of thermal stress reduction method, aiming at the reduction of exterior restraint stress by placing SR-concrete admixed with setting retarder at construction joint between new concrete and old one, the items as follows have been clarified.

(1) Reducing effect of thermal stresses by this method has close relation to setting speed of SR-concrete, namely, to elastic modulus or compressive strength which changes as dosage of setting retarder varies. After several investigations carried out, it is found convenient to correlate SR-concrete for reduction of external restraint stress with its compressive strength at a maximum temperature of new concrete and the target of compressive strength to attain specified reduction ratio is shown in Table 4, although this is concluded from the experimental results within the limited conditions such as mix proportion, thermal transition and size of specimens.

(2) In this construction method, the inclination has been noticed that with increased dosage of setting retarder, the degree of relative displacement between new concrete and old one increases and it is approximately in proportion of distance from the center of specimen. That is to say, by such increase of relative displacement thermal stresses are conceived to be reduced.

(3) On the other hand, decrease of joint strength due to increase of relative displacement is comparatively small and is nearly same as in the case of conventional method. And joint strength tends to decrease in proportion to distance from the center of specimen approximately.

(4) Reduction of thermal stress by this method is more effective to tensile stress which is caused later than to compressive stress caused at the beginning by external restraint.

5. POSTSCRIPT AND ACKNOWLEDGEMENTS

In this paper, the auther has described reduction mechanism, joint strength and dertermination method of target compressive strength for the required stress reduction referring to the method for reduction of external restraint stress with a layer of SR-concrete.

However, there is room for further investigation with respect to the adequate application of this method to actual construction as the study results hereinstated are concluded from the limited instances of sectional area and rigidity ratio between new concrete and old one, mix proportion and thermal history as well as the results obtained with rather small specimens.

Nevertheless, the study results herein-presented would serve useful as a guideline for designing for the time being while further study of actual application is required in order to refine this method of thermal stress reduction to the extent of general applicability.

The auther wishes to express his sincere appreciation to Dr. Manabu Fujii of Kobe University as well as to Dr. Tokio Kondou of Technical Research Institute of JDC Corporation for their valuable suggestions for the study. Acknowledgements are also extended to messrs. Kiyoshi Asanuma and Suehiko Yokota of JDC Corporation for their collaboration in the experiment and analysis of data obtained.

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