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STUDY ON CONCRETE SURFACE MICROCRACKS WHEN USING PERMEABLE FORMS

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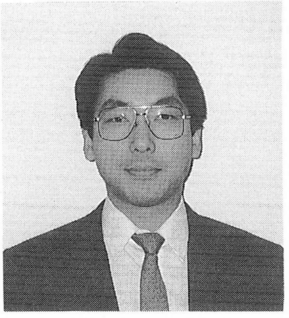

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SYNOPSIS

The use of permeable form concreting methods has become the subject of attention as a technology to improve concrete durability. This paper describes the possible causes of both microcracks and their visible quasi-hexagonal patterns, and their effects on concrete durability, which may occur with the use of permeable forms, based on the results of the authors' experiments. It is found that these phenomena are mainly caused by the difference in drying shrinkage between the outer surface layer of concrete and the inner concrete, and that the occurrence of a quasi-hexagonal pattern is closely related to the efflorescence phenomenon. As these cracks are extremely small in width and depth, it can be considered within the scope of this experimental study that they will not affect concrete durability.

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1. INTRODUCTION

As the problem of early deterioration of concrete due to salt damage has surfaced, a demand has risen for technology to improve the durability of concrete structures. It is at such a time that there has been much interest shown concerning improvement of the durability of concrete through the use of permeable forms.

A permeable form is made with its surface to be in contact with concrete, or sheathing board, faced with a material such as fabric to make it possible for air and water to escape from concrete placed inside the form.

The idea of facing the surface of the sheathing board with fabric or other material so that the surface of the concrete will have an attractive finish has been in existence for a long time, but with recent permeable forms, special innovations have been made on the fabric and drainage method, and efficiencies of deairing and draining have been improved.

Permeable forms are also referred to by names such as dewatering forms and fabric-lined forms, but will be called permeable forms in this paper.

The reason permeable forms have drawn attention is not only because air bubbles are removed to make the concrete surface prettier. It is because durability is improved through less notching of the cross section due to residual air voids, and lowering of water-cement ratio at the surface layer of concrete through discharge of excess water from the form so that a dense layer of thick paste is formed near the surface resulting in a concrete into which it is difficult for carbon dioxide and salts to penetrate from outside.

Various kinds of permeable forms have been commercially available since several years ago. Their performances have been reported in literature[1]; some have been authenticated in examinations by official agencies[2] and have gained high regard.

However, while such advantages have been recognized, it has been pointed out in a paper[3] that when using permeable forms, so-called crazing consisting of microcracks of irregular quasi-hexagon-shaped patterns (hereafter referred to as "quasi-hexagonal pattern") appeared on the surface of concrete after stripping of forms (Photo. 1).

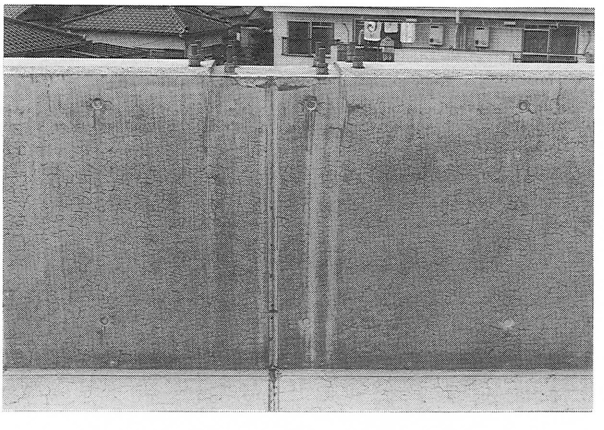

Photo. 1 Quasi-hexagonal crack pattern formed on railing of viaduct wall

The authors witnessed the test project reported in the abovementioned paper and had the opportunity of visually inspecting the test specimen and the actual structure over time. As a result of observations, it was seen that elapse of time is required for the quasi-hexagonal pattern to appear, with a tendency for parts with microcracks occurring at the concrete surface becoming changed in color and conspicuous.

This paper, based on the results of experiments conducted by the authors, considers the causes of microcracks and quasi-hexagonal patterns occurring at concrete surfaces where permeable forms had been used, and aims to show what effects they have on durability of concrete.

2. OUTLINE OF EXPERIMENTS

In planning tests, although permeable forms and constructor were different, the case of the beforementioned paper in which microcracks and quasi-hexagonal patterns similarly occurred was used as reference.

2.1 Fabricating of Specimens

The specimen shape was that of a wall as shown in Fig. 1, and the thickness was made 25 cm.

As the permeable form to be used in the experiments, a type with holes opened in the sheathing board and faced with a double-woven fabric (Fig. 2) was selected, and this was used at the front surface of the specimen. Decorative plywood (JIS Class 2) was used for the back and side surfaces (Photo. 2).

2.2 Mix Proportions of Concrete

The mix proportions of the concrete used in the experiments are given in Table 1. Concrete divided into two lifts was cast directly into forms from an agitator truck. Consolidation was done using an internal vibrator (ϕ 32 mm) with consolidation time 200 sec per cubic meter.

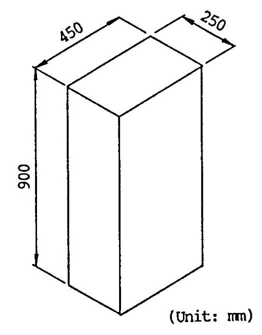

Fig. 1 Specimen configuration

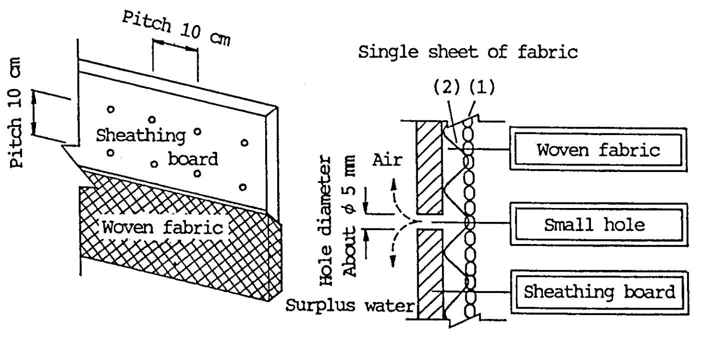

Fig. 2 Construction of permeable form used in experiments

Photo. 1 View of assembled forms

Table 1 Mix proportions of concrete used in experiments

Nominal strength	Range of slump (cm)	Range of air cont. (%)	Water-cement ratio W/C (%)	Sand-agg. ratio s/a (%)	Unit content (kg/m³)				
					Water W	Cement C	Fine agg. S	Coarse agg. G	Admixture Ad*
210	8± 2.5	4± 1	60	46.1	163	272	846	1,153	0.544

Ad* : Standard type air-entraining, water-reducing agent

Table 2 Factors and levels used in experiments

Factor	Level				
	1	2	3	4	5
A: Form stripping time	M_1	M_0	M_2		
B: Curing method	No curing	Sprinkler curing	Indoor curing	Fan curing	Membrane curing

2.3 Selection of Characteristic Values

In view of the beforementioned case, it was thought that early stripping of forms after placing of concrete, the rapid drying of the concrete surface after stripping, and the effect of using superplasticizers had had effects. Therefore, (1) the moisture content at the surface portion of concrete, and (2) quantity of microcracks occurring at the concrete surface were selected as characteristic values to be used in the experiments.

2.4 Setting Up of Factors and Levels

The stripping time of forms (A) and the method of curing (B) were taken up as factors, and the experiments were made two-factor experiments (two-way classification) with no repetitions. Further, the numbers of levels were three for A and five for B. Accordingly, there were 15 kinds of combinations of levels of A and B (Table 2). Further, to investigate the effects when adding superplasticizer at the jobsite, similar experiments were conducted twice with and without addition of superplasticizer (target slump 15 cm, with superplasticizer having a naphthalene sulfonate compound as the main ingredient used).

2.4.1 Form Stripping Time

The stripping time of forms was calculated based on estimated temperature according to the following equation[4]:

$$M = \Sigma\ (\theta + A)\ \Delta t$$

where, M: estimated temperature (℃ · h)
θ: concrete temperature during Δt hours (℃)
A: constant = 10 ℃
Δt: time (h)

The outside air temperature on average during the previously-mentioned case was taken to be 10℃ , and with the case of stripping forms on the second day after placing the concrete as the reference (M_0), half of that (M_1), and further, assuming a case of outside air temperature 20℃ on average and stripping forms on the fifth day after placing concrete, three times that (M_2), were taken.

(1) M_1 = 480℃ · h [= (10+ 10) x 24]
(2) M_0 = 960℃ · h [= (10+ 10) x 48]
(3) M_2 = 2,880℃ · h [= (20+ 10) x 96]

2.4.2 Curing Method

(1) No curing: left standing outdoors
(2) Curing by water sprinkler: after sprinkling water outdoors for 5 days, left standing untouched
(3) Indoor curing: left standing outdoors for 2 days, then sprinkled once with water, and left standing indoors
(4) Fan curing: after blowing on air for 5 days (air velocity[5]: 5 m/s), left standing untouched
(5) Membrane curing: after applying membrane curing agent (vinyl ethylene acetate base) outdoors, left standing untouched

2.5 Method of Measuring Moisture Content of Concrete Surface Portion

The moisture content at the surface portion of concrete (average moisture content to depth of 4 cm from the surface) was measured using a moisture meter manufactured by K Co. (measuring system: high-frequency volumetric type (20 MHz), measuring range: 0 to 12% (concrete), measuring accuracy:± 0.5%) (Photo. 3).

Measurements were made only at the permeable form sides, at the locations shown in Fig. 3. The times of measurement were daily up to 1-week age, at 2 and 3 weeks, and then at 1 month and 3 months.

2.6 Method of Measuring Microcracks at Concrete Surface

Microcracks formed at the concrete surface were observed with a shop microscope (magnification: 20 powers) manufactured by P Co., traced with oil-base ink on a transparent plastic plate (making a frame of 10 cm x 10 cm), and the lengths of cracks inside the frame were measured to obtain the total length (Photo. 4).

Measurements were made at the two locations at the upper part of the specimen shown in Fig. 4, and the average value was taken as the amount of microcracks formed. The times of measurement were ages of 1 week, 1, 3, and 6 months, and 1 year.

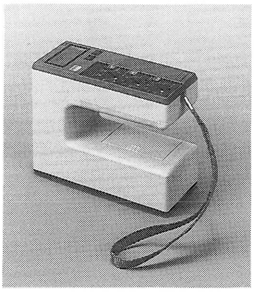

Photo. 3 Moisture meter

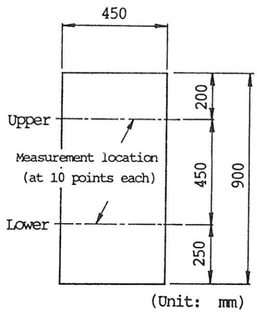

Fig. 3 Moisture content measurement location

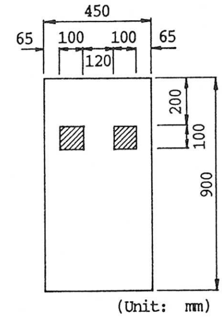

Fig. 4 Area of microcrack measurement

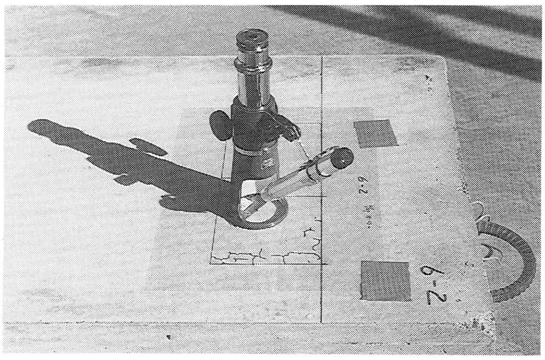

Photo. 4 Measurement of microcracks

2.7 Method of Confirming Occurrence of Quasi-hexagonal Pattern

As a result of observing an actual structure, it was seen that with the elapse of time, the parts of microcracks changed to a wet color over a width of several millimeters and began to be conspicuous as quasi-hexagonal patterns. In view of this, observations were made continuously of the surfaces of specimens to grasp the times when visual confirmation of quasi-hexagonal patterns can be made and their conditions of growth.

3. RESULTS OF EXPERIMENTS

3.1 Moisture Content at Surface Portion of Concrete

The amounts of water discharged from the forms collected at tops of furrings at the bottoms of the permeable forms were about 0.5 to 1.6 ℓ/m^2 and somewhat less than the 2.0 ℓ/m^2 on average in past experiments.

Regarding the moisture content at the surface layer of concrete on the permeable form side, in order to check the influences of the factors (stripping time of forms and method of curing) on the degree of reduction in moisture content after stripping of forms, the rate of moisture reduction calculated by the following equation was used instead of the characteristic value (moisture content):

$$\text{Moisture Content Reduction Rate (\%)} = \frac{A - B}{A} \times 100$$

where, A: moisture content measured at stripping of form (%)
B: moisture content measured at each age (%)

The measured values of moisture contents when stripping forms were 8.5 to 12% (upper limit of measurement) and the range of measured values at the various levels during the period until removal of forms was about 1 to 2%. On the other hand, the moisture contents on the plywood sides measured at the times of stripping forms for the sake of reference had all exceeded the measurement range. The results of calculations of moisture content reduction rates measured at 1-week age and later are shown in Fig. 5.

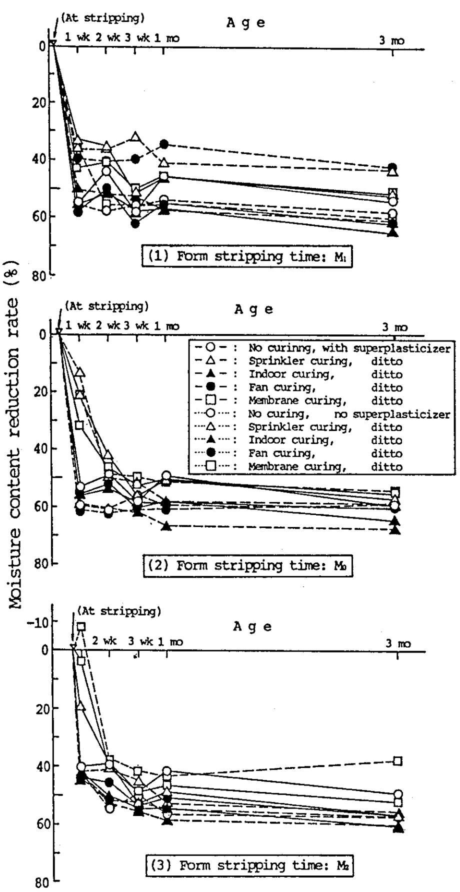

Fig. 5 Rate of moisture content reduction of concrete surface layer

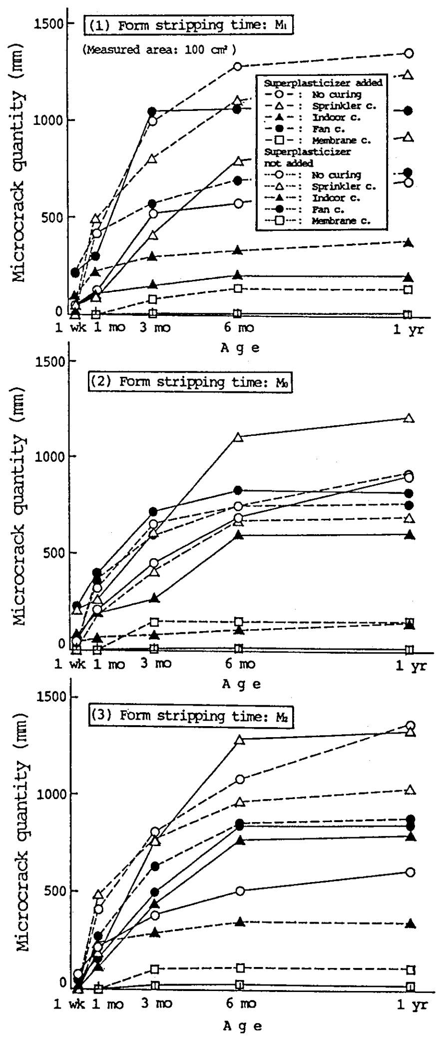

Fig. 6 Results of measurements of microcrack occurrence at concrete surface

Table 3 Results of dispersion analysis of moisture content reduction rate (dispersion ratio F_0)

Factor			Age				
			1 wk	2 wk	3 wk	1 mo	3 mo
Superplasticizer	Added	A: Form stripping time	11.9 ** 19.5 **	11.1 ** 6.61 *	7.98 * 6.06 *	11.9 ** 9.23 *	4.73 * 3.30
		B: Curing method	15.0 ** 49.6 **	18.6 ** 17.4 **	5.59 * 2.12	21.7 ** 23.0 **	9.44 ** 7.48 *
	Not added	A: Form stripping time	- -	3.12 4.53	2.33 5.10	3.47 13.6 **	1.60 6.22 *
		B: Curing method	3.65 1.97	2.70 4.77 *	1.72 3.41	1.56 4.69	1.34 3.63

(Note) 1. F distribution table 5% limiting value: F(2,8;0.05)=4.46, F(4,8;0.05)=5.14
F(2,6;0.05)=3.84, F(3,6;0.05)=4.76
2. F distribution table 1% limiting value: F(2,8;0.01)=8.65, F(4,8;0.01)=10.9
F(2,6;0.01)=7.01, F(3,6;0.01)=9.78
3. * : 5% significance ** : 1% significance
4. Upper level: all curing methods
Lower level: excl. membrane curing
5. -: Dispersion ratio $F_0 < 1$

As a result of carrying out dispersion analyses for the various ages, the values given in Table 3 were obtained as dispersion ratios, F_0, of the various factors. As a result, the individual factors were significant in case of adding the superplasticizer, but in case of no addition of superplasticizer, the effects of the factors were not prominent. Furthermore, considering the use of membrane curing agent, dispersion analyses were made of the two kinds of cases including and not including membrane curing.

Also, in order to investigate the rate of moisture content reduction with and without superplasticizer, verification of the average value for the corresponding two groups (significance level 5%) was done for each age, but there were no significant differences other than for age of 2 weeks.

The following were learned from these results:
(1) The moisture content at the surface layer portion of concrete decreases rapidly in the period up to about 1 week after stripping forms, after which there is a trend to decrease gradually. Since the degrees of reduction in moisture contents were small for specimens cured by sprinkling with water and by membrane compared with other curing methods, it is thought the rapid decline in moisture content after stripping is due to drying.

(2) Whether or not superplasticizer has been used has hardly any effect on the rate of reduction in moisture content at the surface layer of concrete, but there is greater effect on rate of reduction in moisture content of the stripping time of forms and the curing method.

(3) Regarding the effects of period of forms left in place and the curing method on the rate of reduction in moisture content, the case of M_0 shows the trend of the reduction rate to be the highest in case of stripping time of forms, but in case of curing method, there is no given order seen according to age.

3.2 Quantity of Microcracks Occurring at Concrete Surface

The results of measuring the quantities of microcracks at the concrete surface

Table 4 Results of dispersion analysis of microcrack occurrence quantity (dispersion ratio F_0)

Factor			Age				
			1 wk	1 mo	3 mo	6 mo	1 yr
Superplasticizer	Added	A: Form stripping time	2.55 2.82	2.91 3.33	– –	– –	– –
		B: Curing method	3.12 2.22	8.40 ** 2.93	7.40 ** 2.69	14.3 ** 4.45	16.0 ** 4.64
	Not added	A: Form stripping time	1.78 1.87	2.91 3.33	3.20 5.73 *	3.92 5.38 *	4.30 6.18 *
		B: Curing method	1.47 1.36	12.4 ** 3.95	21.0 ** 18.1 **	26.2 ** 20.0 **	32.9 ** 26.7 **

(Note) 1. F distribution table 5% limiting value same as in Table 3
2. * : 5% significance ** : 1% significance
3. Upper level: all curing methods
Lower level: excl. membrane curing
4. –: Dispersion ratio $F_0 < 1$

are shown in Fig. 6. Regarding the two factors taken up in the experiments, as a result of dispersion analyses made for the various ages, the dispersion ratios, F_0 , for the factors were as shown in Table 4. When calculated excepting membrane curing, both factors were significant in case of not adding superplasticizer, but when added, neither of the factors was significant.

Concerning the effect on quantity of microcracks formed depending on whether or not superplasticizer was added, similarly to the rate of reduction in moisture content, verifications of differences in average value of corresponding pairs of sets were made for the various ages from 1 week to 1 year, and there was no significant difference between average values.

The following were learned from these results:
(1) Progress of microcracking at the concrete surface tends to become stopped with elapse of time.

(2) The stripping time of forms has an effect on the amount of microcracks from 1-month age and after, with a trend of decrease in case of M_0 or M_1 .

(3) The method of curing affects the amount of microcracks formed, and as seen in the case of addition of superplasticizer, the influence of membrane curing is especially great, while when membrane curing is done, the occurrence of microcracks becomes extremely small.

(4) Whether of not superplasticizer has been added does not affect the amount of microcracks formed, but the effect on amount of microcracks formed becomes prominent in case of no addition.

Next, with regard to the influence of drying of the surface layer portion of concrete in the occurrence of microcracks, the relationship between rate of moisture content reduction and amount of microcrack occurrence (ages 1 week, 1 month, and 3 months) at the upper part of the specimen (Fig. 3) will be as shown in Fig. 7. Microcracks do not occur until rate of moisture content reduction of around 40%, and begin to occur when exceeding this percentage, and a trend is recognized for the amount of occurrence to become larger as the rate of moisture content reduction becomes higher.

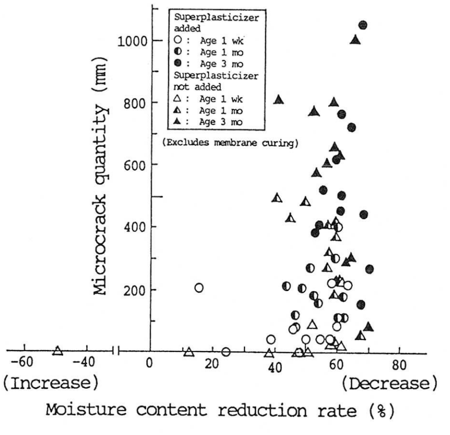

Fig. 7 Relationship of moisture content reduction rate and microcrack occurrence quantity

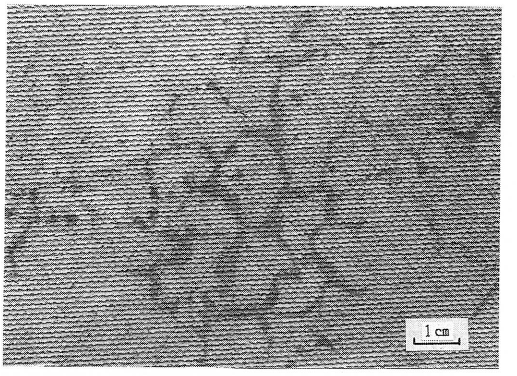

Photo. 5 Quasi-hexagonal pattern formed on concrete surface

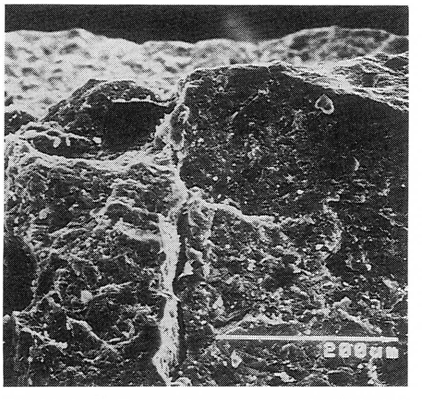

Photo. 6 Photomicrograph of microcracking

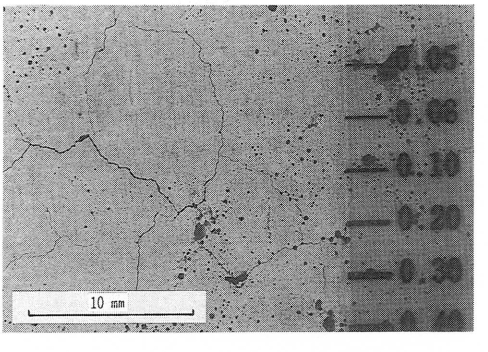

Photo. 7 Quasi-hexagonal cracks (plywood form)

Table 5 State of occurrence of quasi-hexagonal pattern

Test condition			Age measured								
			2 wk	1 mo	2 mo	3 mo	4 mo	6 mo	9 mo	11 mo	1 yr
Superplasticizer added	No curing	M_1					■	■	■ ○	○	○
		M_0					■	■	■		○
		M_2					■	■	■		○
	Sprinkler curing	M_1									
		M_0									
		M_2					□				
	Indoor curing	M_1									
		M_0									
		M_2									
	Fan curing	M_1					■	■	■	○	○
		M_0					■	■	■ ○	○	○
		M_2					■	■	■		○
	Membrane curing	M_1									
		M_0									
		M_2									
Superplasticizer not added	No curing	M_1					□	□	■		
		M_0						□	■		
		M_2					■	□	■ ○	○	○
	Sprinkler curing	M_1									
		M_0									
		M_2					□				
	Indoor curing	M_1									
		M_0									
		M_2									
	Fan curing	M_1	□	□	□		■	■	■		
		M_0	□				■	■	■		○
		M_2					■	■	■		○
	Membrane curing	M_1									
		M_0									
		M_2									

	Semi-dry	Fully dry
Partial	□	○
Whole	■	●

3.3 State of Occurrence of Quasi-hexagonal Pattern

In these experiments, quasi-hexagonal patterns of cracking appeared over the entire surface of the concrete where permeable forms had been used from around the age of 4 months as the surface continued to dry, especially, in the cases of no curing and curing by blowing air (Photo. 5), but the quasi-hexagonal patterns became less conspicuous as drying of the entire surface progressed. However, when as much as a year had elapsed, the quasi-hexagonal patterns, albeit at parts, became visible all of the time. The conditions of occurrence of the quasi-hexagonal patterns after the age of 2 weeks are as shown in Table 5.

4. CONSIDERATIONS REGARDING CAUSES OF MICROCRACK OCCURRENCE

4.1 Features of Microcracks Due to Permeable Forms

An electron photomicrograph of microcracks formed at the surface layer portion of concrete using a permeable form is shown in Photo. 6. The crack width is about 10 μ m, with the depth of cracking, although not clear in this photograph, about 3 mm at maximum according to a photograph taken separately.

Occurrence of microcracking was not local, but was seen over the entire surface of concrete. The density of occurrence was about 130 m/m^2 at maximum within the area of measurement in Fig. 4. This corresponds to a lattice pattern of mesh width of approximately 1.5 cm.

As shown in Photo. 7, there were cracks occurring in a quasi-hexagonal pattern similarly to cases of permeable forms at concrete surfaces where plywood forms were used, but compared with cases of permeable forms, the cracks were open and the widths and depths were greater.

4.2 Estimate of Cause of Occurrence

The case of cracking of mortar applied to finish concrete has been known from the past as an example of occurrence of quasi-hexagonal patterns of cracking. This cracking is said to occur due to shrinkage of the mortar used as finish material being restrained by the substrate concrete having less shrinkage[6]. It is also known that what has the greatest influence on drying shrinkage of concrete is the unit water content, and shrinkage is smaller the less the water content. When unit water contents of mortar and concrete are compared, mortar generally has higher water content and, therefore, the shrinkage is greater. From this, it may be considered that quasi-hexagonal patterns of cracks occurring in the past had been drying shrinkage cracking caused when concrete is restrained so that it cannot shrink freely on drying.

An examination is made here to see whether the microcracks occurring with use of permeable forms can be considered as drying shrinkage cracks.

In case of placing concrete using permeable forms, excess water and air mixed in are discharged outside the form through fabric lined on the surface so that the actual water-cement ratio of the concrete is lowered, and especially, at the surface layer portion (about 5 mm from the concrete surface), the cement content is increased compared with when using plywood forms due to movement of cement particles accompanying drainage[7]. Even when using plywood forms, there is a tendency for less coarse aggregate at the surface layer portion and more mortar, and when permeable forms are used, this tendency will become more prominent.

In case of using permeable forms, it may be considered from the results of these experiments (Fig. 7) that drying of the surface layer portion of concrete has an influence on occurrence of microcracks.

In view of the above, it may be considered that the surface layer portion and the interior of concrete using permeable forms have a relationship similar to the abovementioned finish material (mortar) and substrate concrete, and microcracks occurring with use of permeable forms may also be considered as drying shrinkage cracks. However, the differences from the case of mortar finish is that whereas the mortar finish is of a thickness of about several centimeters, the thickness of the dense mortar layer formed in case of permeable forms is about several millimeters, and the spacing and widths of cracks are extremely small. The reason that crack spacing and width become small is thought can be explained by looking on the mortar layer as "cover" and the internal concrete restraining it as "reinforcement" from the fact that in experiments[8], [9] crack spacing and widths of reinforced concrete members are smaller the thinner the cover.

Further, that almost no microcracking occurs in case of membrane curing is because of the tensile strength of the concrete surface becoming high due to the membrane curing agent (polymer) applied to the concrete surface.

5. CONSIDERATIONS OF CAUSE OF QUASI-HEXAGONAL PATTERN

In these experiments, microcracks at the concrete surface were confirmed by microscope in one week after stripping of forms when permeable forms were used, while quasi-hexagonal patterns appeared at age of 4 months or later, with the patterns gradually becoming visible with passage of time. Microcracks were recognized at roughly the center of the changed color part of wet color making up the quasi-hexagonal pattern (Photo. 8), but there were cases when parts of changed color were not formed even after time had elapsed as in the case of specimens cured indoors.

In contrast, as shown in Photo. 7, cracks formed when using plywood forms had dirt adhered with dark streaks occurring, but changed color portions as in case of permeable forms did not occur. However, microcracks the same as with permeable forms have been reported[10] in case also of using permeable forms, with parts of changed color recognized. This is thought to suggest that it is possible for quasi-hexagonal patterns to occur with conventional forms depending on the concrete materials and mix proportions, and it is not necessarily a phenomenon unique to permeable forms (Photo. 9).

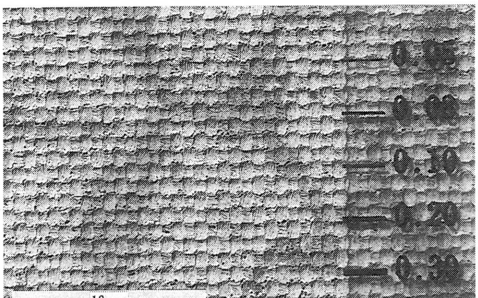

Photo. 8 Quasi-hexagonal pattern (permeable form)

Photo. 9 Quasi-hexagonal pattern (conventional form)

Considerations will be given here regarding the mechanism of microcracked parts changing into quasi-hexagonal patterns with elapse of time when using permeable forms, noting the change in color at the parts of the quasi-hexagonal patterns.

Moisture is evaporating from the concrete surface at all times, and calcium hydroxide which is a hydration product of free lime and calcium silicate in the cement transported together with water is precipitated at the concrete surface. Further, with elapse of time, this is changed to calcium carbonate on being subjected to the action of carbon dioxide in air, and the color becomes white. The so-called "efflorescence phenomenon" has occurred. Occurrence of efflorescence is caused by evaporation of moisture from the surface of a hardened cement object, and it is necessary for as much evaporation as possible to occur under the condition of drying of the surface, and it is said to occur in large quantity when air temperature is low, humidity is comparatively high, and wind speed is of a suitable degree[11].

When cracking has occurred at the surface of concrete, if the crack width is not too large, moisture collects at the crack from capillaries (pores) connecting to the crack through capillary action. Therefore, the concrete very close to the crack, because of the effect of the moisture collecting at the crack, has a moisture content higher than other parts. When the crack width is extremely small, evaporation of moisture from the crack and its neighborhood will be slow, and calcium hydroxide cannot precipitate at the concrete surface, so that the efflorescence phenomenon cannot easily occur. It is the same when rainwater or other water infiltrating into the cracked portion evaporates. Consequently, the color of this part continues to be the darker inherent color of concrete. The cracked portion, if moist, will be a dark, wet color, and will be especially conspicuous just after it has stopped raining. It is thought that because of such a reason, with elapse of time, a darker zone where progress of efflorescence is delayed more than elsewhere is formed in the neighborhood of the crack.

Next, the conditions of occurrence of quasi-hexagonal patterns according to method of curing are considered in relation to the efflorescence phenomenon.

That occurrences of quasi-hexagonal patterns are close to zero with specimens cured indoors is considered to be because cracks are not filled with water as the specimens are placed for long periods indoors where it does not rain so that evaporation occurs from the entire surface and efflorescence has progressed.

The surface of concrete cured by sprinkling water was whitish compared with others, and although microcracks occurred, almost no quasi-hexagonal patterns could be seen. This is thought to have been because through sprinkling of water after stripping forms, drying of the surface layer portions of concrete at early age was suppressed, and compared with specimens other than membrane-cured, the moisture content of the hardened cement object became high and through evaporation of this a large amount of efflorescence had occurred over the entire surface.

With specimens not cured and cured blowing air, microcracks occurred in comparatively large quantities (Fig. 6), and quasi-hexagonal patterns appeared distinctly on both types. This is thought to have been due to the previously-mentioned mechanism.

That quasi-hexagonal patterns did not appear on specimens membrane-cured is considered to have been because there was little occurrence of microcracking.

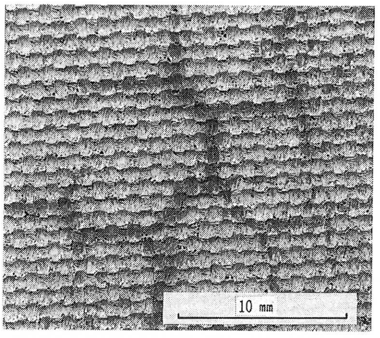

Photo. 10 Natural filling of microcracks

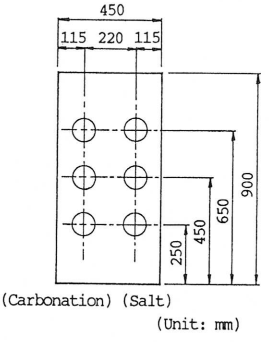

Fig. 8 Coring location

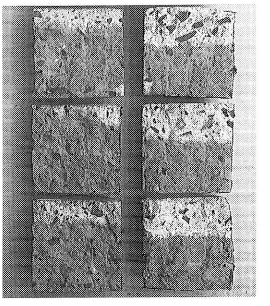

Photo. 11 Example of accelerated carbonation test results (indoor curing)

With regard to the conditions of change in microcracks themselves, a trend can be seen over the long term for the cracks which had been open initially to be gradually filled with precipitated matter (calcium hydroxide)as shown in Photo. 10.

6. CONSIDERATIONS OF INFLUENCE OF MICROCRACKS ON DURABILITY

In many experiments in the past concerning permeable forms, core specimens collected at 28-day age were used and compared with cases of using plywood forms for verification of the effects on durability of concrete in case permeable forms were used. However, questions were not especially raised in these experiments concerning microcracks at concrete surfaces. Therefore, various durability tests were performed irrespective of the existence of microcracks, and it is thought there are no reports at all of the results of various tests carried out on durability using specimens on which occurrence of microcracks had been confirmed.

As can be comprehended from the test results of this study, it may be expected that numerous microcracks will appear on concrete surfaces of about 1-month age unless special curing such as by membrane is carried out. It is thought this suggests that microcracks occurring on concrete surfaces where permeable forms have been used have almost no effect on durability of concrete.

In this study, in order to investigate the influence of microcracks on durability of concrete, core specimens were collected at the locations shown in Fig. 8 from test blocks 1 year old, and salt penetration and accelerated carbonation tests were conducted (the upper part corresponding to microcrack measurement locations). Cores were collected from all test blocks, and at the same time, for the purpose of comparisons, cores were also collected from concrete surfaces where plywood forms had been used, the test blocks having been subjected to no curing and indoor curing.

6.1 Accelerated Salt Penetration Tests

Salt penetration acceleration tests used specimens sealed with epoxy resin at surfaces not contacting forms, and alternate wetting and drying were carried out. For the high-temperature, high-humidity environment, the salt spray testing apparatus specified in JIS Z 2371 on the method of testing corrosion resistance of m

Table 6 Results of measurements of salt penetration depth

(Unit: mm)

			Superplasticizer added			Superplasticizer not added		
			M_a	M_b	M_c	M_a	M_b	M_c
Permeable form	No curing	Upper	19.6	33.0	34.5	40.9	36.7	51.2
		Middle	20.5	15.7	22.0	26.3	35.0	26.1
		Lower	19.3	22.6	16.8	48.5	26.1	26.6
		Av.	19.8	23.8	24.4	38.6	32.6	34.6
	Sprinkler curing	Upper	31.2	39.9	32.2	46.0	19.6	31.1
		Middle	18.9	29.0	23.2	29.1	18.5	20.3
		Lower	20.3	19.7	21.7	27.7	16.7	28.6
		Av.	23.5	29.5	25.7	34.3	18.3	26.7
	Indoor curing	Upper	45.6	43.4	30.8	43.5	30.1	37.8
		Middle	35.4	16.7	27.2	45.9	39.9'	33.5
		Lower	41.3	19.8	20.8	29.5	33.0	24.1
		Av.	40.8	26.6	26.3	39.6	34.3	31.8
	Fan curing	Upper	40.4	39.8	29.2	33.9	32.5	28.6
		Middle	32.5	34.3	29.7	25.1	46.6	30.6
		Lower	25.2	30.8	23.8	26.0	13.6	23.0
		Av.	32.7	35.0	27.6	28.3	30.9	27.4
	Membrane curing	Upper	41.2	39.3	25.9	50.4	48.8	27.1
		Middle	33.9	27.0	21.9	38.2	26.1	29.0
		Lower	25.1	24.2	16.5	34.9	36.5	20.4
		Av.	33.4	30.2	21.4	41.2	37.1	25.5
Plywood form	No curing	Upper	53.6	53.0	54.7	64.6	54.0	62.5
		Middle	56.6	50.4	46.9	54.9	63.9	56.0
		Lower	51.8	49.7	44.9	48.5	55.7	59.5
		Av.	54.0	51.0	48.8	56.0	57.9	59.3
	Indoor curing	Upper	69.8	45.6	51.1	65.9	56.6	70.5
		Middle	53.6	42.4	47.9	54.6	54.4	53.8
		Lower	48.6	43.9	46.5	49.1	50.5	60.9
		Av.	57.3	44.0	48.5	56.5	53.8	61.7

Table 7 Results of measurements of carbonation depth

(Unit: mm)

			Superplasticizer added			Superplasticizer not added		
			M_a	M_b	M_c	M_a	M_b	M_c
Permeable form	No curing	Upper	19.1	17.0	28.6	29.4	15.9	26.2
		Middle	15.3	13.9	20.1	18.9	16.4	13.0
		Lower	18.0	14.4	20.0	23.1	14.8	9.3
		Av.	17.5	15.1	22.9	23.8	15.7	16.2
	Sprinkler curing	Upper	21.8	25.9	22.8	27.1	17.6	18.8
		Middle	16.1	25.4	17.3	20.5	11.1	11.9
		Lower	16.1	18.2	20.4	18.4	9.5	16.7
		Av.	18.0	23.2	20.2	22.0	12.7	15.8
	Indoor curing	Upper	38.8	30.5	35.1	39.3	33.8	22.3
		Middle	37.8	28.8	31.8	37.0	35.6'	13.1
		Lower	38.8	26.0	24.8	26.3	31.6	25.1
		Av.	38.5	28.4	30.6	34.2	33.7	20.2
	Fan curing	Upper	26.1	20.8	28.0	26.8	27.4	14.3
		Middle	22.9	23.0	20.0	21.8	21.0	20.8
		Lower	18.4	17.9	19.7	25.3	14.9	15.9
		Av.	22.5	20.6	22.6	24.6	21.1	17.0
	Membrane curing	Upper	23.0	16.5	23.3	28.5	24.2	20.6
		Middle	23.3	19.4	19.3	24.0	11.8	12.8
		Lower	20.4	16.5	14.5	15.5	17.6	15.3
		Av.	22.2	17.5	19.0	22.7	17.9	16.2
Plywood form	No curing	Upper	39.2	37.2	35.3	40.7	42.0	41.5
		Middle	33.6	32.7	31.3	36.9	35.3	36.1
		Lower	33.9	33.0	36.1	33.5	34.9	35.3
		Av.	35.6	34.3	34.2	37.0	37.4	37.6
	Indoor curing	Upper	47.5	47.9	42.1	45.4	51.5	42.3
		Middle	40.0	38.1	41.4	42.6	46.3	42.6
		Lower	43.7	41.4	39.0	42.7	48.1	44.0
		Av.	43.7	42.5	40.8	43.6	48.6	43.0

etal materials was used spraying salt water of concentration 5%, with the temperature inside the tank 35℃. As for the low-temperature, low-humidity environment, temperature was made 15 ℃ and relative humidity 65%. Cores were split at 3 months after start of testing, and an 0.1% aqueous solution of fluorescein sodium and 0.1 N silver nitrate solution were sprayed on the fracture surfaces and the depths of parts which had turned white were measured.

Table 6 gives the results of measurements of average salt penetration depths for the various specimens. Other than a trend seen for depth of salt penetration becoming shallower the longer the period of forms left in place, the influences of the curing method and whether or not superplasticizer had been used were small. The depth of salt penetration in case of permeable forms as contrasted to the case of plywood forms was 35 to 70% with no curing and about 50 to 70% with indoor curing and the effect of the permeable form could be recognized.

Regarding the influence of microcracks on salt penetration depth, since there was no correlation between them, it is thought hardly any influence exists. This is considered to be because of the shallowness of the microcracks.

6.2 Accelerated Carbonation Tests

In the accelerated carbonation tests, specimens of the same kind as in the accelerated salt penetration tests were placed in a test chamber of temperature 40 ℃, relative humidity 40%, carbon dioxide concentration 10%, and after leaving in the chamber for 3 months, they were taken out and split. Measurement of carbonated depth was done by spraying 1% phenolphthalein alcohol solution on the fracture planes and taking the depths of the uncolored parts (Photo. 11).

Table 7 gives the results of measuring average carbonation depths of the various specimens. In the cases of permeable forms, influences on carbonation depths of the stripping time of forms and the existence of superplasticizer are not recognized, but regarding methods of curing, the rates of progress of carbonation on specimens with curing done indoors were prominent for both permeable and plywood forms. The reason that carbonation depth is greater with indoor curing is thought to be because there is practically no supply of moisture such as rainwater to the concrete indoors so that the concrete surface is dried the most and penetration of carbon dioxide increases[12].

The carbonation depths in cases of permeable forms are 40 to 70% for no curing, and about 45 to 90% for indoor curing, and the effect of the permeable forms can be recognized.

Similarly to the results of the salt penetration tests, a correlation between quantity of microcracks occurring and depth of carbonation is not recognizable.

It may be judged from the results of these durability tests that microcracks formed when using permeable forms do not constitute a factor to greatly affect durability properties of concrete.

7. CONCLUSIONS

It was considered in this study that early stripping of forms after placement of concrete and the rapid drying of the concrete surface after stripping, the use of superplasticizers, etc. were influential in causing occurrence of microcracks and quasi-hexagonal patterns. The experiments were conducted taking up the moisture content at the surface layer portion of concrete and the amount of microcracking at the concrete surface as characteristic values, and the stripping time of forms and method of curing as factors, while further, considering whether or not superplasticizer had been used. The causes of occurrence of microcracks and quasi-hexagonal patterns were contemplated based on the results. Further, the effects of microcracks on durability of concrete were studied.

The findings concerning the causes of microcracks and quasi-hexagonal patterns, and the effects of microcracks on durability of concrete gained in this experimental study may be summarized as follows:

(1) It may be considered that the cause of occurrence of microcracks is the drying shrinkage of the dense mortar layer formed at the concrete surface through dewatering.

(2) The method of curing after stripping of forms had a great influence in occurrence of microcracks, whereas the effects of form stripping time and superplasticizer were small. Of the methods of curing, membrane curing had much effect in preventing the occurrence of microcracks.

(3) The rate of reduction in moisture content at the surface layer portion of concrete, in case of addition of superplasticizer, was greatly affected by the period of forms left in place and the method of curing. With regard to the stripping time of forms, the case of M_0 (estimated temperature: 960 ℃ · h) at the various ages of measurement showed a trend of the reduction rate becoming greatest, while with regard to curing method, there was no given order according to the method and a specific trend could not be recognized. As for the relationship between rate of reduction in moisture content and amount of occurrence of microcracking, microcracks began to occur when the rate of reduction exceeded a certain limiting value, while further, as the rate of

reduction in mortar content became higher, a tendency for amount of microcrack occurrence to be increased was recognized.

(4) The method of curing had a large influence on occurrence of quasi-hexagonal patterns of cracking, and it may be considered that efflorescence phenomena in the neighborhood of microcracks are related to appearance of quasi-hexagonal patterns. When forms are stripped at an early stage, curing by sprinkling of water is a practical method of inhibiting occurrence of quasi-hexagonal patterns.

(5) Microcracking was not a factor greatly affecting durability of concrete. This is thought to have been because of the shallow depth of microcracks.

In the results of these experiments, significant differences did not exist between the respective values with and without addition regarding superplasticizers, but with regard to the influence on the effects of the two factors (stripping time of forms and method of curing), the case of addition with regard to moisture content reduction rate, and the case of no addition with regard to amount of microcrack occurrence, were respectively prominent. It is considered that studies concerning these influences of superplasticizer comprise a topic of future investigation.

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References

[1] For example, S. Kobayashi, "Recommendation of the Use of Permeable Forms," Cement and Concrete, No. 519, May, 1990
[2] Technology Center for National Land Development, "General Civil Engineering Construction Methods and Technical Examination Certification," March, 1988
[3] M. Yamada, E. Miki, Y. Nakayama, "Concrete using Fabric-lined Form," Cement and Concrete, No. 517, March, 1990
[4] Japan Society of Civil Engineers, "Standard Specifications for Concrete [Construction Volume]," p. 146, October, 1986
[5] Cement Association of Japan Concrete Experts Committee, "Influences of Drying at Early Age in Various Properties of Concrete," Cement and Concrete, No. 466, December, 1985
[6] A. Baba, "Actual State of Cracking Damage - Exterior Walls -," Concrete Journal, Vol. 20, No. 11, November, 1982
[7] Y. Kasai, K. Sato, K. Suga, M. Nagano, "Cement Contents of Surface Concretes Using Permeable Forms and Plywood Forms," Cement Association of Japan Review of the 42nd General Meeting Technical Session, 1988
[8] Y. Kakuta, "Maximum Crack Width of Reinforced Concrete," Concrete Journal, Vol. 8, No. 9, September, 1970
[9] P. Gergely, L. A. Lutz, "Maximum Crack Width in Reinforced Concrete Members," ACI SP-20, 1968
[10] T. Tagami, "Claims against Concrete Series (Part 6), Cracks Formed in Concrete," Concrete News, No. 23, October, 1989
[11] T. Saito, S. Ishii, "On Efflorescence of Cement Products," Journal of Research of the Onoda Cement Co., Vol. 19, Part 1, No. 70, p. 88, 1967
[12] T. Saeki, H. Ohga, S. Nagataki, "Mechanism of Carbonation of Concrete," Proceedings of the Japan Concrete Institute, 11-1, 1989