INFLUENCES OF PENETRATIVE CURING ON PROPERTIES OF CEMENTITIOUS MATERIALS

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Influences of penetrative condition of curing water on properties of cementitious materials were investigated. In a large-size specimen with a low water-cement ratio (W/C), both the mixing water and penetrative water at standard water curing are not sufficient to complete the hydration of the entire specimen. Therefore, curing conditions were studied to improve the properties of the specimens at any distances from the surface during hydration process. When W/C is low, specimens cured with water containing AE-admixture, which has low surface tension, and water under high pressure was able to improve the degree of hydration and strength more than those subjected to the standard water curing.

Key Words: water penetration, hydration, non-evaporable water, self-desiccation, high pressure water curing, low surface tension water curing

1. INTRODUCTION

The properties of hardened paste result from the reaction between cement and mixed water. The penetration of water, when added from outside, is important to improve the degree of hydration. However, in a large-size specimen with a low water-cement ratio (W/C), the curing water cannot penetrate enough to completely fill pores that formed during the hydration reaction, resulting in different degree of hydration and self-desiccation in the near-surface-area and in the bulk of the specimen[1]-[3]. For this reason, it has drawn our attention to study and work on the significance of penetrative curing conditions.

Proper curing is essential to achieve a discontinuous pore structure, which is the discontinuity in capillary pore network that formed during the hydration in concretes. With W/C lower than 0.45, the discontinuous pore structure will be formed easily. The discontinuous pore structure is important for a durable concrete, as it will limits both water and ion ingress into the concrete structures[4]. Based on the measurement of permeability, Powers has concluded that capillary pore discontinuity is a function of both W/C and degree of hydration: a higher W/C requiring longer hydration time to achieve a discontinuous capillary pore structure[5]. He, therefore, suggested to cure concretes until this discontinuity is achieved, as further "saturated" curing would result in vain unless any additional water flows into the concrete[6]. Based on a microstructure model for cement paste

hydration, Bentz and Garboczi suggested a critical capillary porosity threshold value of approx. 20%, below which capillary pores show discontinuity[7]. At any starting W/C ratio, if the hydration can reduce the initial capillary porosity less than 20%, a discontinuous pore structure will be formed.
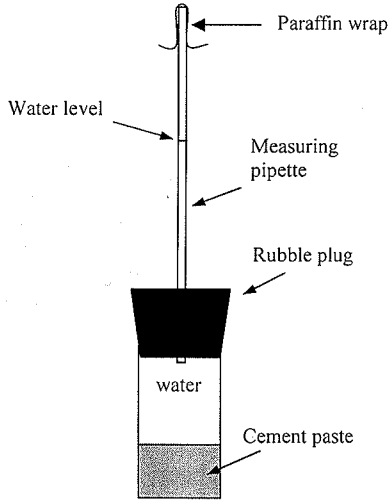
Self-desiccation takes place when the pores created by the hydration are not supplied with water from the surrounding environment during the curing process[1], and empty pores are created within the microstructure[8].

Although many curing methods have been proposed[4],[6],[9],[10], no research defines the degree of self-desiccation in terms of water penetration capability in concrete. We also proposed the curing methods using low surface tension water and high pressure water to improve water penetration which is evaluated by the degree of self-desiccation. Those curing methods have been reported in our previous work[11]-[13].

In this paper, influences of penetrative conditions of curing water on the properties of cementitious materials were experimentally investigated. The results of experiment were expressed by measuring the amount of water penetrated into the hardened cement paste at various distances from the surfaces. The measurement was compared with hydration reaction, degree of self-desiccation, volume fraction of each component in hardened cement paste, non-evaporable water, and strength factors. Additionally, the mortar specimens were also experimented to verify the strength.

Table 1 Physical properties and mineral composition of cement

Cement	Fineness (cm²/g)	Density (g/cm³)	Mineral Composition (mass%)					Ig. Loss (mass%)
			C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	
OPC	3290	3.16	62.4	13.5	8.3	8.5	2.4	2.01

Fig.1 Measuring method of chemical shrinkage -Experiment (2) a)-
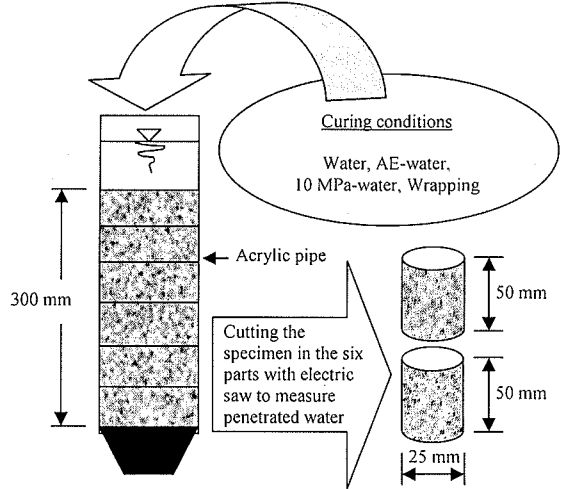
Fig.2 Measuring method of the penetrative curing water in hardened cement paste -Experiment (2) b) 2)-

2. OUTLINE OF THE EXPERIMENT

(1) Materials

An ordinary Portland cement with characteristics as shown in **Table 1** was used. For the compressive strength test of mortar, the crushed sand (density: 2.58 g/cm³, absorption: 2.28 %) was used as a fine aggregate. An air entraining and high range water-reducing agent were used for specimens with a W/C of 0.2, 0.25 and 0.3. A Silicone Antifoaming Agent was added to reduce the air content in all type of pastes. The air content of pastes was decreased less than 0.1%. Alkyl-ether based air-entraining agent of 1% added with water, in accordance with JIS A6204 of, was used in AE-water curing to reduce surface tension of curing water. This amount is quite larger than the case of concrete mixture. The surface tension of water for AE-water curing was approx. 38 mN/m which is nearly one half of that used in standard water curing. It was measured by Du Nouy surface-tension meter at a room temperature of 22°C and 50 % RH.

(2) Experimental procedures
a) Test method for chemical shrinkage

Mass of a glass vessel was measured with accuracy of 0.1g. This value was referred to as
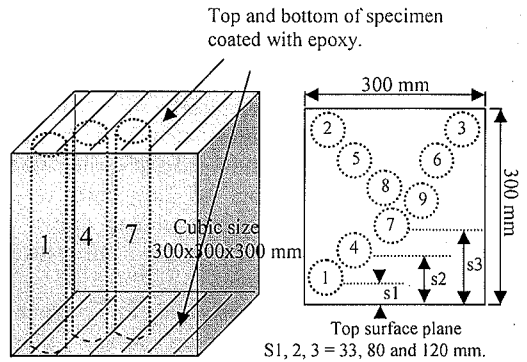
Fig.3 Test of compressive strength with core specimens -Experiment (2) c)-

$M_1(g)$. The cement paste with a W/C of 0.2, 0.3, 0.4 and 0.6 were placed in the glass vessel with a thickness of approx. 10mm in height, and then the total mass of cement paste and the vessel were measured with an accuracy of 0.1g. This value was referred to as $M_2(g)$. The vessel was filled slowly with water in order to prevent the disturbance of the interface, and then a measuring pipette was inserted perpendicularly into the sample vessel through a rubber plug. Subsequently water was added from the upper inlet of the measuring pipette by a funnel or washing bottle to a measuring range, and then
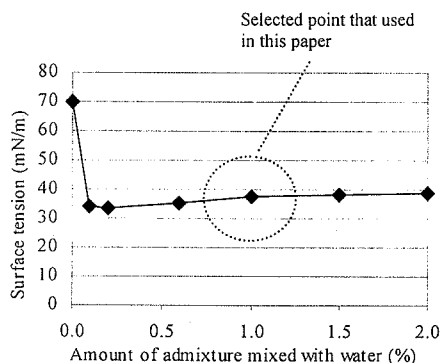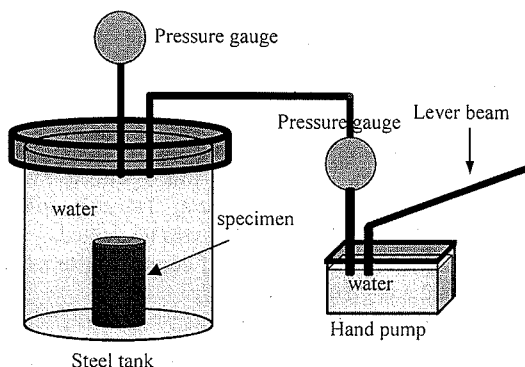
Fig.4 Surface tension of AE-water

Fig.5 High pressure water curing

sealed the upper parts of measuring pipette with a paraffin wrap and this specimen was stored in the curing room as shown in **Fig.2**. The initial water level in the pipette was read with an accuracy of 0.05 ml. This value was referred to as H_0 (ml) when starting the measurement. Subsequently the values of water level in the pipette were read during hydration. These values were referred to as H_n (ml). The chemical shrinkage of hardened cement paste can be calculated using Eqs.(1) and (2).

b) Test method for water penetration in hardened cement paste

In this test method, the masses of each hardened cement pastes, as prepared in 1) and 2) at a room temperature 22°C, were measured by M_{21}(g). Subsequently, the specimens were stored for 24 hours in an oven at a temperature of 105°C and their masses were measured again (M_{105}). Finally, the specimens were stored for 24 hours in an electric furnace at a temperature of 950°C and then their masses were measured (M_{950}).

1) Cement paste with a W/C of 0.2, 0.3, 0.4 and 0.6 were placed in acrylic pipes with a diameter of 25 mm and with a paste height of 5, 10, 20, 30, 50, 70 and 100 mm. The specimens were cured after one day using standard water curing. The penetrated water was determined after 1, 3, 7, 14, 28 and 90 days by taking them out from the acrylic pipes and their masses were measured.

2) Cement pastes with a W/C of 0.25, 0.40 and 0.6 were placed in the acrylic pipe with a diameter of 25 mm and with a paste height of 300 mm. The specimens were cured after one day using four different types of curing: the standard water curing (Water curing), the low surface tension water curing (AE-water curing), the high pressure water curing (10MPa-water curing) and the sealed curing (Wrapping). The penetrated water was determined after 3, 7 and 28 days by cutting the specimen in six parts with electric saw as shown in **Fig.2** and then

their masses were measured immediately. The mass of specimen was scarcely changed by drying at this cutting, because the side of specimen was still covered by the acrylic pipe.

In a specimen with a W/C of 0.4 and 0.6, slight bleeding occurred. However, it will be ignored at this stage because the main point of this experiment is to emphasize the penetration of curing water into a low W/C specimen.

c) Test method for penetrating water in mortar

Mortars with a W/C of 0.25, 0.4 and 0.6, and a sand/cement (S/C) mass ratio of 1.58, 2.00 and 2.56 were used respectively. The paste/sand volumetric ratio of 0.932 was common to all the W/C. The mortars were placed in the mould (300 x 300 x 300 mm in size) and then stored in a curing room for 24 hours. After demolding, the top and the bottom of the specimen were coated with an epoxy resin to protect the penetration of water through the surfaces. The coated specimens were exposed to the different types of curing at a temperature of 20 ± 3°C: 1) Water curing, 2) AE-water curing, 3) 10MPa-water curing and 4) Wrapping. After 28 days, the specimens were cored as shown in **Fig.3** and then cut into 3 parts and subjected to the stress-strain test.

d) Curing conditions

1) Water curing: The Water curing with a surface tension approx. 70 mN/m was used as the standard water curing.

2) AE-water curing: Alkyl-ether based air-entraining agent of 1% added with water. Its surface tension was approx. 38 mN/m as shown in **Fig.4**. In this experiment, the surface tension of AE-water curing was scarcely changed at any ages.

3) 10MPa-water curing: a steel tank with a diameter of 500 mm and a height of 600 mm closed with a steel lid was used to maintain a pressure of 10MPa (its maximum capacity). The pressure was maintained by using a hand pump as shown in **Fig.5**.

4) Wrapping: plastic sheets were used to prevent the water movement through the surfaces.

(3) Calculation of specific volume of each component in hardened cement paste

In this research, air content was reduced by adding Silicone Antifoaming Agent. Thus, in all cases of calculation, the air content was neglected.

The chemical shrinkage ratio of cement paste as described in 2.a is given by Eq.(1)[1].

$$S_{hyn} = \frac{H_n - H_0}{V_p} \times 100 \ (\%) \qquad (1)$$

where S_{hyn} is chemical shrinkage ratio at an age n, H_0 (ml) and H_n (ml) are water level at the start and at the age n and V_p is the volume of cement paste as given by Eq.(2)[1].

$$V_p = \frac{(M_2 - M_1) \times ((W/C)/D_w + 1/D_c)}{W/C + 1} \ ml \qquad (2)$$

where M_2 is the mass of cement paste and glass vessel, M_1 is the mass of glass vessel, and D_c is density of cement = 3.16 g/cm³.

The total volume of the paste per unit mass of cement ($V_{p/c}$) is given by Eq.(3)[2].

$$V_{p/c} = 1/D_c + (W/C)/D_w \ \ cm^3/g \qquad (3)$$

where D_w is the density of water = 1 g/cm³.

The volume of hydration product per unit mass of cement reacted ($V_{hp/c}$) is obtained by considering the special case of a fully hydrated paste having the critical W/C and given by Eq.(4)[2].

$$V_{hp/c} = (1/D_c + (W/C^*)/D_w) \times \alpha \ \ cm^3/g \qquad (4)$$

where W/C* is critical W/C of 0.38 below which complete hydration cannot occur, and α is the degree of hydration.

The volume of unreacted cement per unit mass of cement ($V_{uc/c}$) is shown in Eq.(5)[2].

$$V_{uc/c} = 1/D_c(1 - \alpha) \ \ cm^3/g \qquad (5)$$

The maximum degree of hydration α_{max} or DH_{max} for a paste with a W/C $\leqq$ W/C* can be calculated in two cases[2]:
1) An unrestricted supply of water is available during curing given by

$$DH_{max} = (W/C)/0.38 \ \ Unseal \ sample \qquad (6)$$

2) If no such water is available, the degree of hydration is limited to the amount of water presented initially

$$DH_{max} = (W/C)/0.44 \ \ seal \ sample \qquad (7)$$

where 0.44 is the minimum required W/C to complete the hydration. At the complete hydration, non-evaporable and gel water are typically approx. 0.23 and 0.21, respectively.

The porosity of hydration product (P_{hp}) can be calculated by dividing the volume of gel pores per kg of reacted cement by that of hydration product and given by Eq.(8)[2].

$$P_{hp} = V_g \times m_g / [V_c + (W/C^*/D_w)] \qquad (8)$$

where V_g is specific volume of gel water = 1 cm³/g, m_g is the mass of gel water per unit mass of cement, V_c is the specific volume of cement paste that is equal 1/D_c.

Specific volume of non-evaporable water (V_n) is obtained by taking the volume of hydration product less those of the cement from which it was formed and the gel water, and dividing by the mass of non-evaporable water as shown in Eq.(9)[2].

$$V_n = [(W/C^*)/D_w - V_g m_g]/m_n \ \ cm^3/g \qquad (9)$$

where m_n is the mass of non-evaporable water per unit mass of cement = 0.23.

The volume of evaporable water per unit mass of cement ($V_{ew/c}$) is obtained by the amount of gel water and capillary water that can be evaporated at 105°C from the experiment (2).b, and given by Eq.(10)[2,3].

$$V_{ew/c} = \frac{(M_{21°} - M_{105°})/D_w}{M_{950°}} \ \ cm^3/g \qquad (10)$$

where M_{21} is the mass of specimen at room temperature, $M_{105}°$ and $M_{950}°$ are the mass of the specimen after heating for 24 hours at 105°C and 950°C, respectively.

The non-evaporable water contains nearly all chemically combined water. This water has a vapor pressure lower than that of the ambient atmosphere and the quantity of such water is in fact a continuous function of the ambient relative humidity. The volume of non-evaporable water per unit mass of cement ($V_{new/c}$) can be determined by the loss upon drying at temperatures from 105°C to 950°C. It can be expressed by Eq.(11)[2,3].

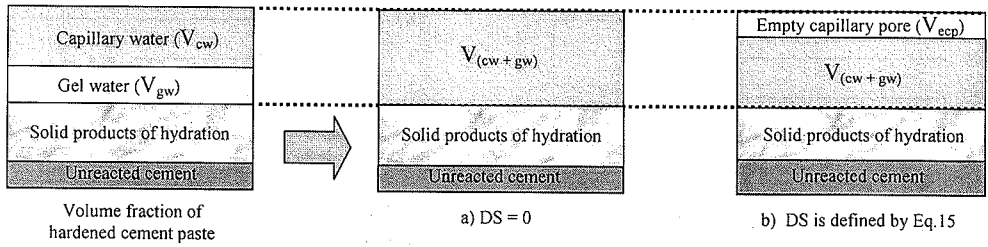Fig.6 Consideration on degree of self-desiccation (DS)

$$V_{new/c} = \frac{M_{105°} - M_{950°}}{M_{950°}} \times V_n \quad cm^3/g \qquad (11)$$

The volume of gel water per unit mass of cement ($V_{g/c}$) is obtained by the mass of gel water per unit mass of cement in a fully hydrated paste, typically approx. 0.21 as given by Eq.(12)[2].

$$V_{g/c} = 0.21\alpha \quad cm^3/g \qquad (12)$$

The volume of capillary water per unit mass of cement ($V_{cw/c}$) is obtained by the amount of capillary water and penetrated water from outside the specimen. It can be expressed by Eq.(13).

$$V_{cw/c} = V_{ew/c} - 0.21\alpha \quad cm^3/g \qquad (13)$$

Degree of hydration (*DH*) is obtained by the proportionality between the amount of non-evaporable water and the solid volume of the cement paste where the former volume can be used as a measure of the quantity of the degree of hydration. It can be expressed by Eq.(14).

$$DH(\alpha) = \frac{M_{105°} - M_{950°}}{M_{950°}} \times 100/23 \quad \% \qquad (14)$$

where 23% is the content of non-evaporable water at the complete hydration[2,3].

In **Fig.6**, a degree of self-desiccation (DS) can be defined as the volume of empty capillary pore (V_{ecp}) per the total volume of capillary water (V_{cw}), gel water (V_{gw}), and empty capillary pore (V_{ecp}). It can be expressed by Eq.(15).

$$DS = \left(\frac{V_{ecp}}{V_{cw} + V_{gw} + V_{ecp}}\right) \times 100 \% \qquad (15)$$

DS also depends on the capability of curing water to fill pores created by hydration. If capillary pores and gel pores are filled with water, DS=0 as
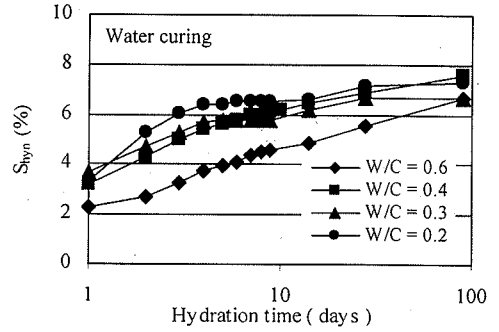

Fig.7 Relation between chemical shrinkage and hydration time
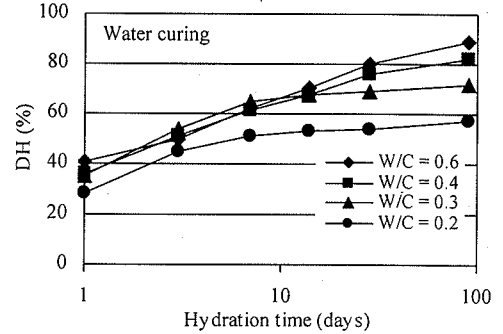–Experiment (2) a) with Eqs.(1) and (2) –

Fig.8 Relation between degree of hydration and hydration time
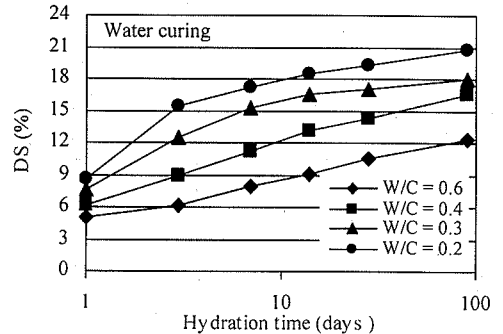–Experiment (2) b) 1) with Eq.(14) –

Fig.9 Relation between Self-desiccation and hydration time
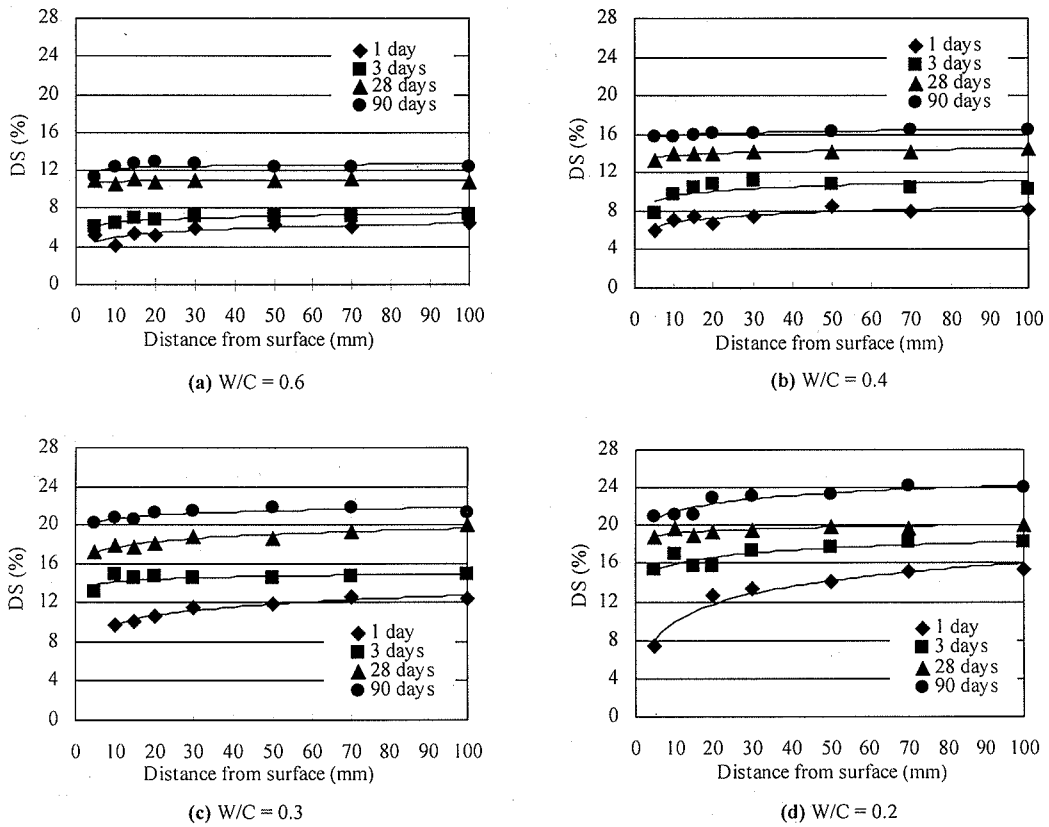–Experiment (2) b) 1) with Eqs.(3)-(15)–

(a) W/C = 0.6

(b) W/C = 0.4

(c) W/C = 0.3

(d) W/C = 0.2

Fig.10 Relation between degree of self-desiccation and distance from surface of specimen during hydration process, maintained by Water curing -Experiment (2) b) 1) with Eqs.(3)-(16)-

shown in **Fig.6a**. Otherwise, during the hydration process, DS is defined by Eq.(15), as shown in **Fig.6b**. In this research, DS for the cement investigated can be calculated by Eq.(16)[8)-10)].

$$DS = (1 - \frac{V_{ew/c}/V_{p/c}}{1-(V_{hp/c}-V_{g/c}+V_{nc/c})/V_{p/c}}) \times 100\ \% \quad (16)$$

3. RESULTS AND DISCUSSION

(1) Chemical shrinkage and degree of hydration

The chemical and physical changes that occur during hydration are accompanied by a reduction in absolute volume. The combined volume of the liquid and solid components after hydration is less than the initial volumes of water and anhydrous cement. The chemical shrinkage for cement paste in different W/C is shown in **Fig.7**. The change of chemical shrinkage for cement paste with W/C of 0.2 and 0.3 was very large at the early stage, but it decreased after approx. four or five days and became blunted after 28 days due to the absence of

enough water to react with cement. The change of chemical shrinkage of cement paste with W/C of 0.4 and 0.6 lasted slowly after 28 days until the hydration completed.

The degree of hydration (DH) for pastes with different W/C is shown in **Fig.8**. DH for specimen with W/C of 0.2 and 0.3 increased very slowly after four or five days and finally becomes blunted after 28 days because of the lower content of water than that necessary to continue the hydration. The cement pastes with W/C of 0.4 and 0.6 seemed to have enough water to continue the hydration reaction even after 28 days.

(2) Effect of W/C on degree of self-desiccation

Most of the hydration products are initially colloidal and as hydration continues the surface area of the solid phase largely increases and a large amount of free water can be absorbed through this surface. However, in the sealed systems where the absorption and dehydration of water are not allowed, only previously added water will take part in the hydration reaction and the relative humidity within the paste will decrease. This is known as self-
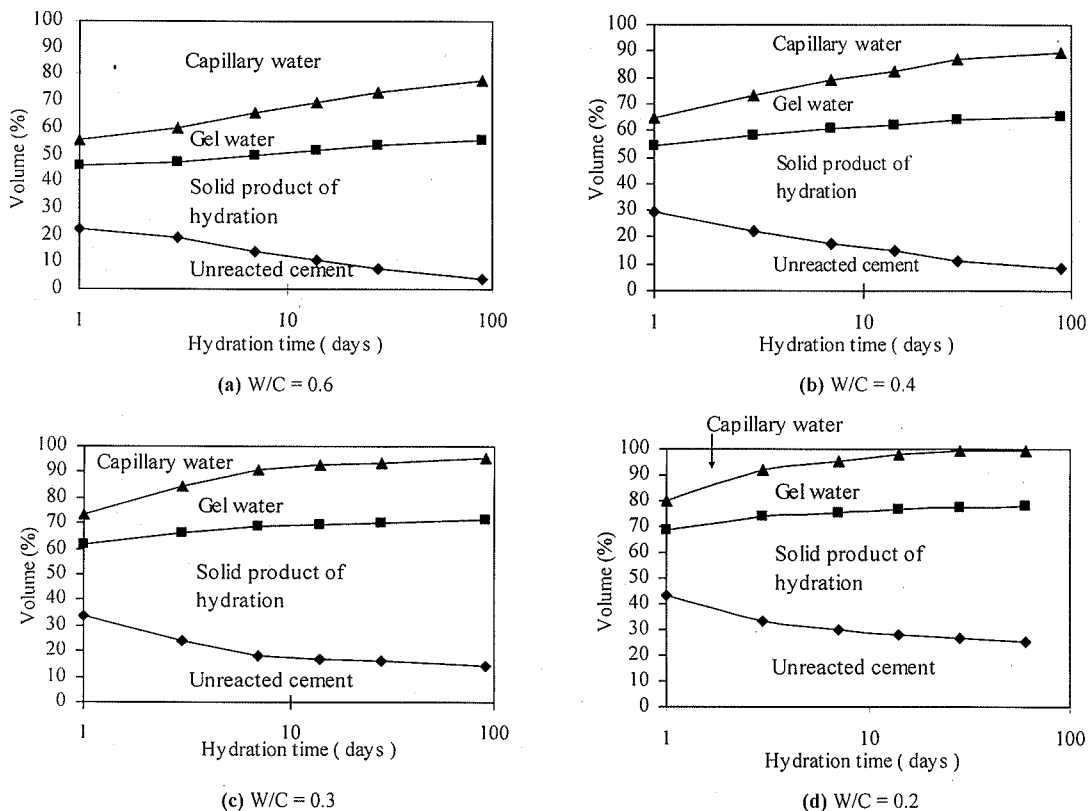
Fig.11 Relation between hydration time and volume fraction of each component (W/C=0.6, 0.4, 0.3 and 0.2) with thickness of 5 mm specimen, maintained by Water curing -Experiment (2) b) 1) with Eqs.(3)-(14)-

desiccation. Since gel can form only in water-filled space, self-desiccation leads to a lower degree of hydration comparing to a moist-cured paste. The amount of free water in hardened cement bulk gradually decreases as the hydration proceeds and fine pores are formed in hardened cement.

The degree of self-desiccation of specimens with different W/C is shown in **Fig.9**. It was calculated from the hardened cement pastes with thickness of about 5 mm. The specimen with W/C of 0.2 shows larger range of self-desiccation during the hydration while that with W/C of 0.6 shows small range of self-desiccation. The change in DH became blunted after 28 days for the specimens with W/C of 0.2 and 0.3 because the near-surface-area became hardened and impenetrable for the water from outside. However, the change in DS still gradually increased because the inside of specimens there remained a little water to react with cement and the empty pores were formed. Likewise, in the specimen with W/C of 0.6, the near-surface-area became hardened during the hydration, and the water penetration to fill pores was partly obstructed. Therefore, it is thought that DS is gradually increased until 12%

after 90 days as shown in **Fig.9**. The hydration increases the gel content and, in mature and dense paste, the capillaries may become segmented by the gels and interconnected solely by the gel pores. The absence of continuous capillaries may be obtained by a combination of suitable W/C and moist curing of sufficiently long time. Thus, if a specimen with a low W/C is not given more water from the outside, the larger range of self-desiccation during hydration may occur.

(3) Effect of distance on degree of self-desiccation

The degrees of self-desiccation at any distance from surface of specimen during hydration process by Water curing are shown in **Fig.10**. In the specimens with a W/C of 0.3 and 0.2, a larger rang of self-desiccation occurred as distance increased. Especially after one day of hydration of specimen with W/C of 0.2, the degree of the self-desiccation of the specimen at the distance of 5 mm from surface is about 6% while that of 100mm is about 16%. The degree of self-desiccation at 90 days of 5 mm with W/C of 0.3 and 0.2 are about 20% and 21%, and that of 100 mm is about 22% and 24% as
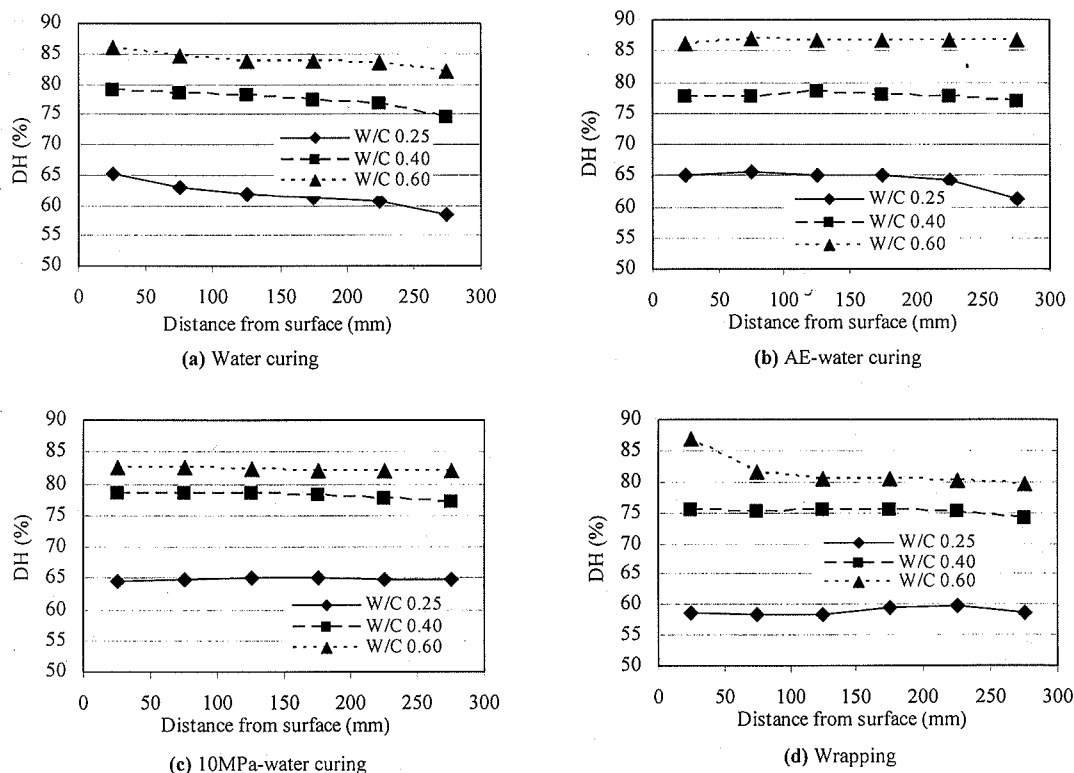
(a) Water curing

(b) AE-water curing

(c) 10MPa-water curing

(d) Wrapping

Fig.12 Relation between degree of hydration and distance from surface of specimen at 28 days-Experiment (2) b) 2) with Eq.(14)-

shown in **Fig.10c** and **Fig.10d,** respectively. The specimens with W/C of 0.3 and 0.2 do not have enough water necessary to react with cement so the penetrating water from outside is important to proceed the hydration reaction. The water from outside cannot penetrate to the middle part of specimen if its thickness is too large. For this reason, the larger distance of specimen shows larger self-desiccation. However, the specimens with W/C of 0.6 and 0.4 have enough water to complete hydration reaction, and the water from outside can as well easily penetrate into the specimens, regardless of specimen thickness. In this case, the degree of self-desiccation was low as shown in **Fig.10a** and **Fig.10b**.

(4) Volume fraction of each component in hardened cement paste

It can be assumed that hydrated cement paste comprises unhydrated cement, solid hydrates, gel water, capillary water and air. The volume fraction of each component changes during the progress of hydration reaction, and consequent the volume of gel pore increased but capillary pore decreased. In this experiment, the volume fraction was calculated from a hardened cement paste with a thickness of 5 mm. It was assumed to be saturated by water curing during the hydration, although a few empty capillary pores are occurred. The volume fractions of each component are shown in **Fig.11**.

The gross space available for the products of hydration consists of absolute volume of the dry cement together with the volume of water added to the mix. The volume content of hydration products changes with the hydration time and it is related directly to the W/C. The amounts of evaporable water and unhydrated cement decrease while the amounts of solid hydration products and gel water increase during hydration. The hydration of specimens with W/C of 0.3 and 0.2 became slower after seven and three days as shown in **Fig.11c** and **Fig.11d**, respectively. It is known that the complete hydration cannot occur if W/C is less than 0.38 in the standard water curing. The hydration became slower when capillary water became less than 15 % of the total volume of hardened cement paste as shown in **Fig.11**. The progress of hydration became more smoothly for the specimen with W/C of 0.6 and 0.4 than that with lower W/C as shown in **Fig.11a** and **Fig.11b**, because of greater amount of water available for hydration reactions.
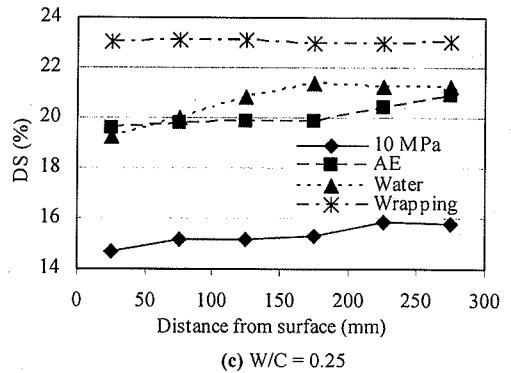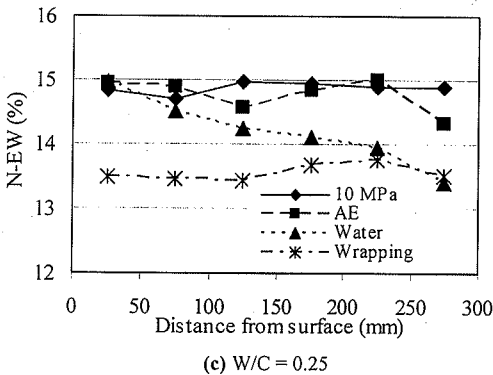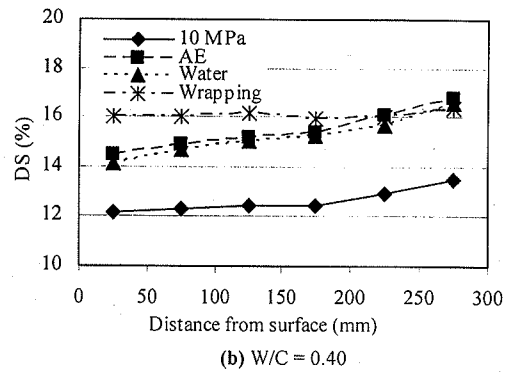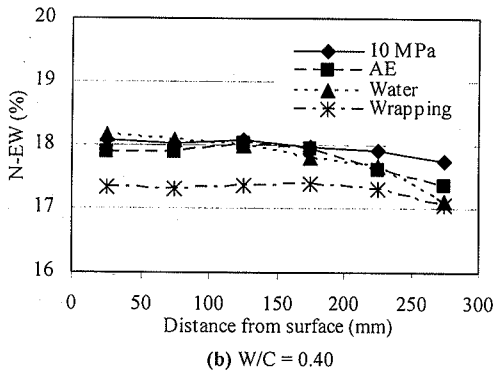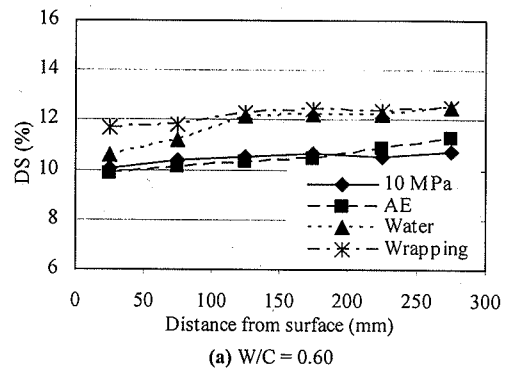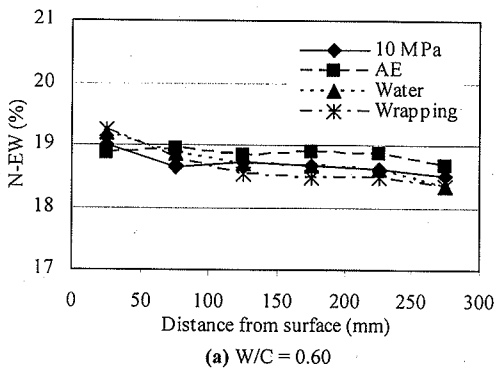
Fig.13 Relation between non-evaporable water and distance from surface of specimen at 28 days
-Experiment (2) b) 2) with Eqs.(9) and (11)-

Fig.14 Relation between self-desiccation and distance from surface of specimen at 28 days
-Experiment (2) b) 2) with Eqs.(3)-(16)-

(5) Effect of distance with any types of curing on degree of hydration

The content of non-evaporable water (explained in a next section), relative to that in a fully hydrated paste of the same cement, was used as a measure of the degree of the hydration according to Powers-Brownyard model[14]. The degree of hydration calculated from Eq.(14) for any distances of the specimen with W/C of 0.25, 0.40 and 0.60 after 28 days are shown in **Fig.12**. The different degrees of hydration, especially in the specimen with a low W/C, were found for the four types of curing used in

this investigation. It could be seen that for the specimen with W/C of 0.25 treated by AE-water curing or 10MPa-water curing, the hydration progressed more than those subjected to the standard water curing and sealed curing. However, for the specimen under AE-water curing, the degree of the hydration was about 65 % at a distance smaller than 175 mm, and then slightly decreased at larger distances of specimen as shown in **Fig.12b**. For the 10MPa-water cured specimen, the degree of hydration remains approx. 65 % regardless of the distance from the surface as shown in **Fig.12c**,

probably due to the penetration of curing water into the specimen. The figure of about 65% is equal to the maximum degree of hydration calculated by Eq.(6). Therefore, it can be thought that the hydration could not progress more than this figure. The degree of hydration in the specimens with W/C of 0.40 and 0.60 was not so affected by the types of curing.

(6) Effect of distance and method of curing on non-evaporable water content

The amount of non-evaporable water increases as hydration proceeds, but in a saturated paste, non-evaporable water can never exceed one half of the total water. In well-hydrated cement, the non-evaporable water is about 18 per cent by mass of the anhydrous cement and this proportion rises approx. 23 percent in the fully hydrated cement[3].

During cement hydration, external water is absorbed by the hydrating cement in a way to compensate the chemical shrinkage. The penetration of curing water into the specimen is important to continue the hydration reaction because the complete hydration reaction cannot occur if W/C is less than 0.38. The content of non-evaporable water, calculated from Eq.(11) for any distance on the specimen with W/C of 0.60, 0.40 and 0.25 after 28 days are shown in **Fig.13**. In the case of sealed curing, non-evaporable water contents were approx. 13.5%, 17.3% and 18.5% for the specimen with a W/C of 0.25, 0.40 and 0.60, respectively. The non-evaporable water content for any distance from the surface to the middle part of the specimen with W/C of 0.25 clearly shows the effect of the types of water curing as shown in **Fig.13c**. It can be seen that for the specimen treated by AE-water curing or 10MPa-water curing, the non-evaporable water contents were larger than that cured with the standard water curing. The specimen with W/C of 0.60 and 0.40 are not so affected by the type of curing as shown in **Fig. 13a** and **Fig.13b**.

(7) Effect of distance with any types of curing on degree of self-desiccation

In a specimen with dense microstructure or with large section, water can penetrate only into the layers closer to the surface of the specimen even under water curing. Thus the central part of the specimen may be subjected to self-desiccation. The degree of self-desiccation, calculated from Eq.(3)-(15), for any distance from the surface of specimen treated with different types of curing is shown in **Fig.14**. The types of curing have a significant effect on the degree of self-desiccation, especially in a low W/C as shown in **Fig.14c**. When cured with water under high pressure (10MPa-water), water was able
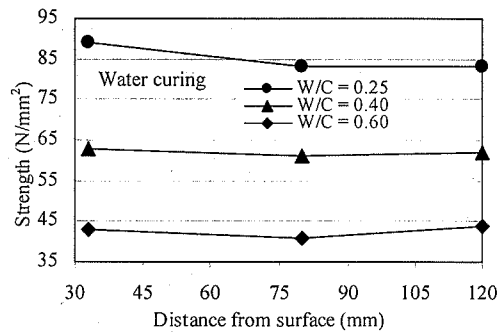

Fig.15 Relation between strength and distance from surface of specimen at 28 days -Experiment (2) c)-
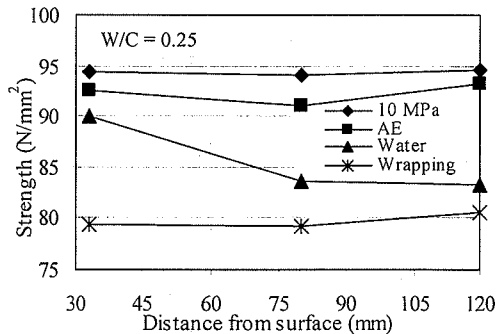

Fig.16 Relation between strength and distance from surface of specimen with any types of curing at 28 days -Experiment (2) c)-

to penetrate deeper into the specimen to fill pores created during hydration than with another types of curing. The experimental results showed that the 10MPa-water curing, comparing with sealed curing (wrapping), was able to reduce the degree of self-desiccation about 2 %, 4 % and 8 % for specimen with W/C ratio 0.60, 0.40 and 0.25 respectively.

In case of AE-water curing, the hydration reaction of specimens is higher than in the Water curing especially in the low W/C specimens as shown in **Fig.12a and Fig.12b**. However, a degree of self-desiccation was not so affected because the more hydration progresses, the more empty pores can be formed. If the empty pores are not filled with water, the degree of self-desiccation may become higher.

(8) Effect of distance and method of curing on strength

It is known that large self-desiccation occurs in accordance with a low W/C partly because water from outside cannot penetrate into the middle part of the specimen. Therefore the self-desiccation may be affected strength of mortar in a way of depressing the hydration. The strength of the mortar specimen with Water curing at different depths was shown in
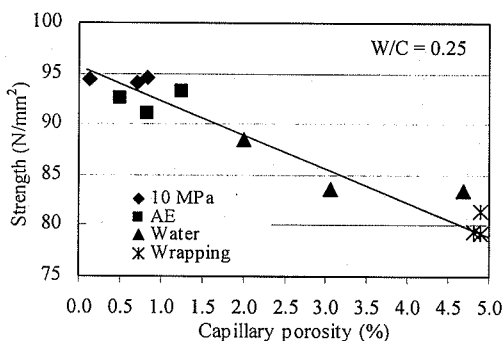
Fig.17 Relation between strength and capillary porosity at distances of 33, 80 and 120 mm from surface with any types of curing at 28 days -Experiment (2) c)-

Fig.15. For the specimen with W/C of 0.25, it was found that the higher the distance from surface of specimen, the lower the strength became. While, the specimens with W/C of 0.4 and 0.6 seemed to have enough water to complete the hydration reaction as the strength of specimen is less dependent on the distance from the surface.

The effect of curing method on strength with low W/C is shown in **Fig.16**. The largest difference in strength was found for the specimen treated with high pressure water curing (10MPa). In the case of the AE-water curing, strength of specimens was higher than those cured with the standard water and sealed curing. These effects could be attributed to the higher degree of hydration and non-evaporable water content and the lower degree of self-desiccation that were presented in section 3.(5), 3.(6) and 3.(7).

Moreover, the relation between strength and capillary porosity that was calculated from the specimens in **Fig.16** at each distances is shown in **Fig.17**. The capillary porosity (%) was calculated by $100 \times (V_{p/c}-V_{hp/c}-V_{uc/c}) / V_{p/c}$ referring to Eqs.(3)-(5). From this relation, it was found that the higher the porosity, the lower the strength became.

4. CONCLUSIONS

Curing of supplying additional water to a specimen during hydration has large influences on properties of cementations materials. The following conclusions regarding to influences of penetrative curing were obtained in this study:
1) For the hardened cement pastes with low W/C, such as W/C of 0.20, 0.25 and 0.30, it was found that the mixing water was unable to fill pores formed as a result of hydration reaction, and to penetrate into the central part of hardened cement pastes. A larger self-desiccation occurs in the

middle part of specimens and the progress of hydration became slower.
2) At any distance from surface to middle part of the specimen with a low W/C, different degree of hydration and self-desiccation due to the lack of hydration were shown. Additionally, the strength in the central part of specimens was lower than in the near-surface-area specimens.
3) The high pressure water curing was able to develop the degree of hydration of specimen in a deep area, around 0-300 mm, more than the other curing method, especially at a low W/C. The degree of self-desiccation becomes lower and strength became higher.
4) Because of the low surface tension of AE agent, the AE curing water was able to penetrate well into the specimen, in the distance less than 175 mm from the surface area, more than that with the standard water curing, especially at a low W/C.
5) The high-strength concrete with low W/C that treated by the standard water curing clearly showed difference in degree of hydration and self-desiccation in the bulk and in the surface layer. Consequently, it is not suitable to apply the same curing condition as applied to the normal concrete because of the difference in surface tension. The degree of the penetration of water into the specimen and degree of self-desiccation were different by the curing water. Further investigations to find the appropriate curing condition as standard for the high-strength concrete, are needed. Nevertheless in this paper, it was found that high pressure water curing and low surface tension water curing was able to develop strength of specimens more than that with the standard curing, especially at a low W/C ratio.

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