Changes in Pore Structure and Enhanced Durability of Concrete by the Use of Permeable Forms

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Synopsis

Permeable forms are designed to drain excess water contained in the concrete immediately after their placement. Removal of excess water not only decreases the water-cement ratio of the surface concrete, but increases the density of the concrete, and eventually enhances its durability. However, few studies focus on the characteristics of pore structure, namely, the relationship between changes in the volume and distribution of capillary pore and the durability of concrete by the use of permeable forms. In this study, investigations were made paying attention to changes in pore structure on past data obtained from tests conducted on permeable forms. The data included pore size distribution, cement volume distribution, depth of accelerated neutralization, salt infiltration and surface strength. The investigations led to the following findings:

1) Use of permeable forms decrease the percentage of pore volume, especially that ranging between 50 nm and 2 μm.
2) In the case of pore size ranging between 50 nm and 2 μm, correlations can be seen between the decrease in pore volume and such properties as neutralization, chloride ion penetration and surface strength.

KEYWORDS: permeable forms, pore structure, capillary pore, pore volume, durability

1. Introduction

Of the water which is used for concrete, the quantity of the water which is necessary for the hydrating reaction to the cement is about 25 % of the cement weight for the combination water which combines with the cement chemically, and is about 15 % for the gel water which adheres to the minute particle surface and contributes to the mutual combination of particles. It is thought that it is about 40 % in amount[1]. Water in excess of that 40% is used mainly to improve the workability of the concrete. As for much of the excess water, it evaporates gradually during the process of hardening and drying of concrete, leaving a pore. When the pore volume increases, the strength decreases and the durability for the neutralization, chloride ion penetration and so on decreases. When thinking of this, excess water is convenient for concrete if it exists only at the time of casting the concrete, and disappears when casting finishes, coming to the outside of the concrete. Also, for air bubbles (mainly, entrapped air) in concrete, to be discharged at the same time by discharging excess water to the outside of the form, air bubbles and honeycombs in the concrete surface are remarkably reduced[2].

As for the permeable forms, to achieve such a purpose, various types have been developed by each company and serve the practical use[3]. Much related study, too, is reported[4,5,6,7,8]. However, few studies focus on the characteristics of pore structure, namely, the relationship between changes in the volume and distribution of capillary pore and the durability of concrete by the use of permeable forms[4]. The authors have reported the result of the experiment about the permeable forms several times including the test results such as the pore size distribution[9,10,11]. However, it was a report about independent test results and as for the relation between the change of the pore structure and the durability, it was a simple comment only. In this study, investigations were made paying attention to changes in pore structure on past data obtained from tests conducted on permeable forms, adding the result of the unreported experiment to the contents of the paper[11](in this paper,experiment B) which the authors reported already.

2. Experiment outline

2.1 Specimens and Test items

Experiment A and experiment B were carried out independently as for the permeable forms almost simultaneously. The characteristic of each experiment is described below.

Experiment A used the ready-mixed concrete of 21-8-20BB(required strength 21N/mm^2, required slump

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8cm, maximum size of gravel 20mm, using blast-furnace slag cement typeB). The specimen size is 1300mm×700 mm×1500mm height. Two specimen were made, one specimen was made using permeable forms for 2 sides (1300×1500mm) and the other specimen was made only from usual plywood forms.

Experiment B used the ready-mixed concrete of 21-8-20BB. The specimen has the shape of retaining wall with 1200 mm height. One specimen was made by using usual plywood forms and five specimens (symbols D0, D1, D2, D3, D4) were made by using permeable forms with the same shape. Five specimens using permeable forms were made by repeated permeable forms (the vertical surface and the slope). Incidentally, as for specimen D0, it shows the specimen of 1st casting which used a permeable form. D1 shows that the specimen of 2nd casting and of 1st repeated use, D2 shows the specimen of 3rd casting and of 2nd repeated use. The outline of the specimen is shown in Fig.1. The test items were pore size distribution, cement volume distribution, depth of accelerated neutralization, chloride ion penetration amount, surface strength, volume of removed excess water. Investigations were made paying attention to changes in pore structure.

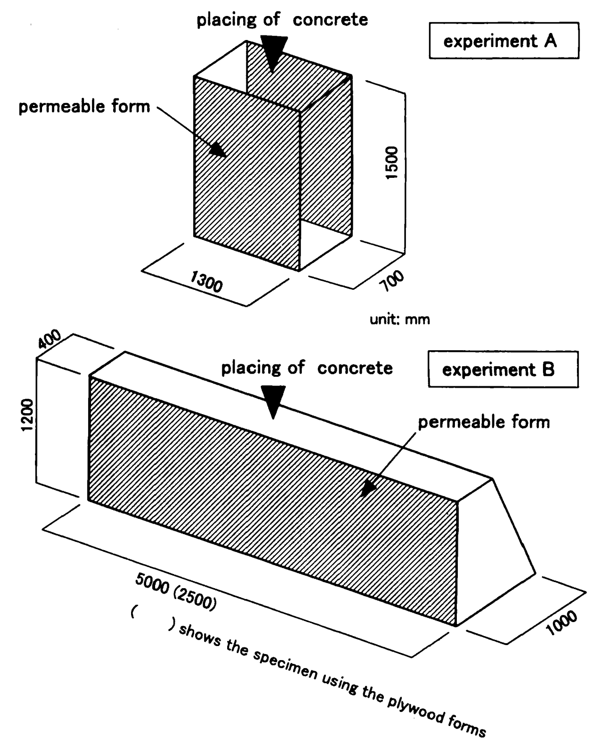

Fig.1 Outline of the specimen

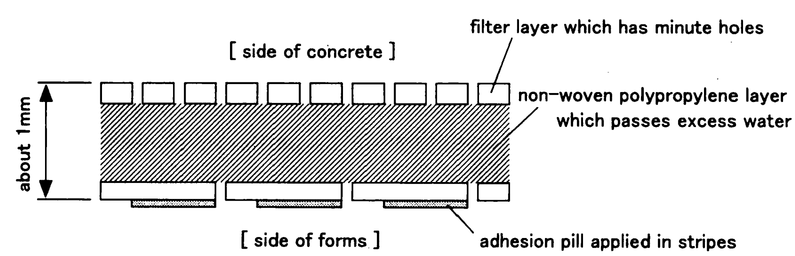

Fig.2 Structure of the water permeable sheet

2.2 Permeable forms

The permeable forms are made by a water permeable sheet and a plywood form. The water permeable sheet is about 1mm thickness. The water permeable sheet is non-woven polypropylene and the surface on the side of concrete had been treated to improve removability at the time of removal of forms and to form the filter layer which has a minute hole. The surface on the side of forms (the back of the water permeable sheet) had an adhesion pill applied in stripes to facilitate the sticking-in of a sheet to the forms. The structure of the water permeable sheet is shown in Fig.2.

2.3 Materials and Mix proportion of concrete

Materials and mix proportion of concrete in each experiment are shown in Table 1 and Table 2.

2.4 Test methods

Measurement of the pore size distribution: The core test pieces (ϕ 10×15cm) were cut off from each specimen after of 4 weeks. In experiment A, one core was cut off from each specimen (one from permeable forms, one from plywood forms) at 750 mm height. In experiment B, we gathered one (one from plywood forms, one from each permeable forms of D0, D2, D4) from the lower part (the 400 mm height) of the vertical surface. Until the examination begins, it is cured at 20 ℃, in 60%R.H.. The specimen for the measurement underwent decompression drying (0.5KPa) for 24 hours after making a hydrating reaction stop using acetone on the 31st day (experiment B is the 30th), and it was used in the examination.

The pore size distribution was measured by using a mercury porosity-meter. In experiment A, a pore size distribution was measured every layer about 0-5 mm, 5-15 mm, 15-30 mm, 30-50 mm, 50-100 mm from the surface of the test concrete. In experiment B, a pore size distribution was measured every layer about 0-10mm, 10-30mm, 30-50mm, 50-100mm.

Table 1. Materials of concrete

	experiment A	experiment B
cement	Portland blast- furnace slag cement (typeB)	
fine aggregate	sea sand	pit sand
coarse aggregate	crushed stone	crushed stone
chemical admixture	AE Water Rdeucing Agent	

Table 2. Mix propotion of concrete

	W/C (%)	s/a (%)	Unit content (kg/m^3) C	W	S	G	Adm
experiment A	57.0	45.5	299	170	801	1023	2.99
experiment B	59.0	45.1	280	165	812	1034	2.80

Measurement of the volume of removed excess water: Measurement of the volume of removed excess water was as follows. In the permeable forms, drain holes were provided for the removal of excess water from the form which was stuck with a water permeable sheet. The volume of removed excess water in the permeable forms was measured as a total with volume of removed excess water from drain holes and which was drained along the water permeable sheet from the footing of the forms. In the plywood forms, the volume of removed excess water which leaks from the footing of the formswas measured. Measurement went until the removal ended approximately (4-6 hours after concrete casting).

The diameter of the drain hole is 9 mm. In experiment A, 12 drain holes at every 100mm horizontally were provided at positions of 200 mm, 650 mm, 1100 mm in height from the bottom tip of the specimen. In experiment B, 8 drain holes at every 100mm horizontally were provided at positions of 100 mm, 525 mm, 950 mm height of the panel (standard panel size is 900 mm widthx 1200 mm height) of the permeable forms of the vertical surface. Absorbed water and keeping water at the water permeable sheet or the plywood forms is not considered.

Measurement of the cement volume distribution: The core test pieces (ϕ 10x15cm) were cut off from each specimen after 4 weeks. In experiment A, one core was cut off from each specimen (one from permeable forms, one from plywood forms) at 750 mm height. In experiment B, one (one from plywood forms, one from each permeable forms of D0, D2, D4) from the lower part (the 400 mm height) of the vertical surface was gathered. Until the examination began, they were cured at 20 ℃, in 60%R.H.. In experiment A, cement volume about 6 layer of 0-5mm, 5-15mm, 15-30mm, 30-50mm, 50-100mm, 100-150 mm layers from concrete surface was estimated. In experiment B, cement volume about 5 layer of 0-10mm, 10-30mm, 30-50mm, 50-100mm, 100-150mm layers from concrete surface was estimated.

The examination of the cement volume distribution was carried out according to The Cement Association of Japan concrete specialty committee report F-18 (Method of chemical analysis for estimating the mix proportion of hardening concrete). But, there were shells in the fine aggregate (sea sand) of test concrete in experiment A, and there was calcium carbonate in the coarse aggregate of test concrete in experiment B. So, it is considered that the estimation of the cement volume from calcium oxide quantity by this method caused a big difference, and in this experiment, it was estimated with silicon dioxide. Incidentally, the result which analyzed silicon dioxide about the cement and the aggregate to have used for concrete to estimate cement volume was as follows using experiment B as an example.

silicon dioxide quantity of cement ; 25.4 %
silicon dioxide quantity of aggregate ; 0.85 %

But, as for the cement, it is measured by JIS (Japanese Industrial Standards) R 5202 "Method for Chemical Analysis of Portland Cement", and as for the aggregate, fine aggregate and coarse aggregate were crushed minutely respectively and is mixed in equal quantity, it is measured by the abovementioned Cement Association of Japan method.

The accelerated neutralization test: The core test pieces (ϕ 10x10cm) were cut off from the specimen after 6 days in experiment A, one core was cut off from permeable forms, one was from plywood forms at 750 mm height. In experiment B, at the time of 4 weeks, core test pieces (ϕ 10x10cm) were cut off (six in total, one from plywood forms, one from each of the permeable forms of D0, D1, D2, D3, D4) from the lower part (the 400 mm height) of the vertical surface. After cutting off, epoxy paint was applied to the surface except the test form surface of the core and making accelerated neuteralization after drying up indoors.

The accelerated neuteralization test was carried out at the 20 ℃ temperature, 60 % of relative humidity, 5 % of CO_2 concentration. In experiment A, it was measured at accelerated age of 13 weeks, and in experiment B, it was measured at accelerated age of 17 weeks. Test pieces were split at the above mentioned age. The depth to the part which doesn't show red-purple color by spraying alcohol solution of 1 % of phenol phthalein on splitted surface from the surface of the test form was measured.

The chloride ion penetration test: The core test pieces (ϕ 10x10cm) were cut off from the lower part (at the 400 mm height) of the vertical surface about one (one from plywood forms, one from each permeable forms of D0, D1,D2,D3, D4) for each at the time of 4 weeks. After gathering, epoxy paint was applied to the surface except the test form surface of the core, cured in 20 ℃ water 48 hours before examination, and served cycle examination between soaking in salt water and drying.

A chloride ion penetration test was implemented only in experiment B. Penetration was promoted for 4 days by soaking salt water (solution of 3 % chlorination sodium, at 20 ℃ of solution temperatures) and drying for 3 days (by the aerial bathing at 50 ℃) , so 1 cycle was 1 week. After 13 cycle ending, soluble chloride ion was extracted (chloride ion) in concrete from every layer from the surface of the test form about 6 layers (0-5mm, 5-10mm, 10-15mm, 15-30mm, 30-50mm, 50-100mm) from the surface. Chloride ion quantity was measured by ion-chromatography method. Incidentally, the extraction of soluble chloride ion was carried out by drying up for 24 hours by the aerial bathing at 105 - 110 ℃ with the concrete fragment which was cut every layer, by measuring about 2g after shattering to all pass with the sieve of 74μm, being fine, and by adding 200 g of water to this and stirring it for 30 minutes at 50 ℃ .

Measurement of the surface strength(rebound number): At the time of 4 weeks, using Schmidt hammer (NR type), 20 points surface strength (rebound number) was measured at a position of 950 mm height in experiment A, and in experiment B, it was measured at a position of 300 mm height. Incidentally, rebound number changed with the surface strength, and the numerical value of the rebound number was used just as it is and to make the investigation of the data simple, correlation with the pore volume was considered.

3. Results and Consideration

In the permeable forms, the lateral pressure by the weight of concrete becomes the main motive power to discharge excess water in concrete to the outside of the forms. Therefore, it is thought that the volume of removed excess water depends on the difference in the vertical position and that it has a big influence on the change of the durable improvement effect and the pore structure, too.

Using each test result of the cement volume distribution test, the accelerated neutralization test and the surface strength test by the specimen which was gathered in the position (the height) which is the same as the gathering position of the specimen for the pore size distribution measurement as the principle in case of the consideration of the test data, the relationship between the pore volume and the properties of concrete about the permeable forms and the plywood forms was examined.

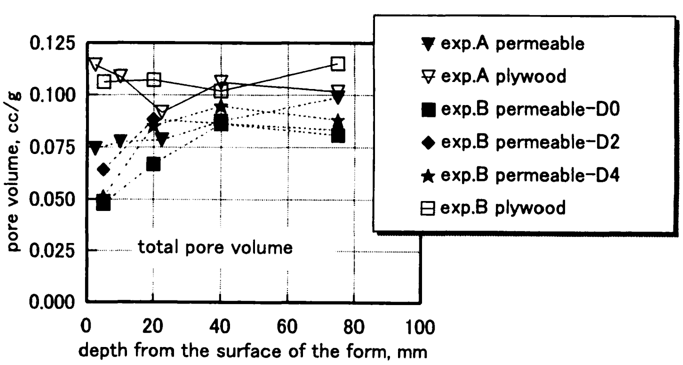

Fig.3 Comparison of total pore volume

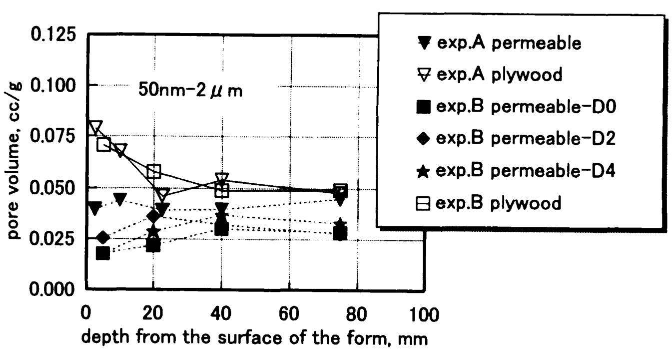

Fig.4 Comparison of 50nm - 2 μ m pore volume

3.1 The pore size distribution and the change of pore structure

The pore size distribution: Generally, in

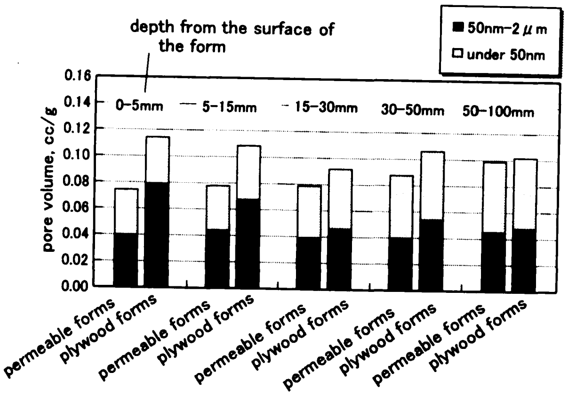

Fig.5 Comparison of pore volume between permeable forms and plywood forms in experiment A

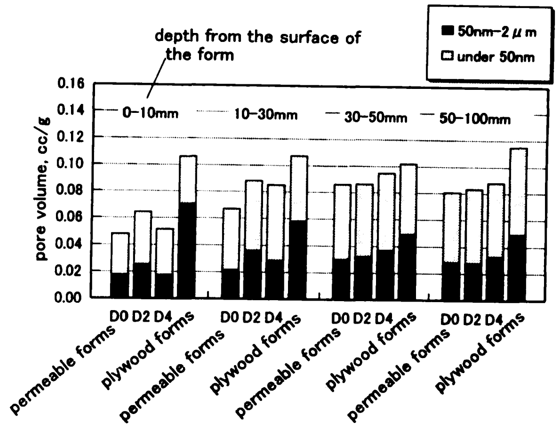

Fig.6 Comparison of pore volume between permeable forms and plywood forms in experiment B

Table 3. Comparison of pore volume ratio in experiments A, B

experiment A	pore volume ratio* in case of using permeable forms				
	1st layer 0-5mm	2nd layer 5-15mm	3rd layer 15-30mm	4th layer 30-50mm	5th layer 50-100mm
50nm-2 μ m	50.3	65.0	84.8	73.5	93.9
under 50nm	97.7	81.8	86.2	91.9	100.0

experiment B	pore volume ratio* in case of using permeable forms					
	1st layer 0-10mm			2nd layer 10-30mm		
	D0	D2	D4	D0	D2	D4
50nm-2 μ m	25.1	35.8	24.8	37.3	62.3	49.6
under 50nm	84.6	109.2	94.7	92.1	105.7	114.4
	3rd layer 30-50mm			4th layer 50-100mm		
	D0	D2	D4	D0	D2	D4
50nm-2 μ m	61.3	65.4	75.5	57.5	56.1	66.7
under 50nm	106.0	102.6	108.9	79.6	84.7	83.9

*pore volume using plywood forms in the same depth layer is ratio 100.

mercury porosimetry, it is possible to measure a pore (capillary pore) in concrete with 3nm - 30 μm diameter[12]. However, actually, pores with 2μm-30μm diameter are very few in concrete, therefore we measure a pore in the range of 3nm - 2μm diameter. In this paper, the diameter of the measured pore were divided into equal to or less than 50 nm, 50nm - 2 μm.

The test result which was compared by dividing the pore size distribution in experiment A, experiment B into total pore volume and 50nm - 2μm pore volume every depth from the surface of the form is shown in Fig.3, Fig.4. It was found that the pore structure of concrete both in experiment A and experiment B changes by using a permeable forms and that total pore volume is decreased conspicuously. Moreover, when considering in the range with pore diameter, it was found that the decrease is mainly due to the decrease of the pore with 50nm - 2μm diameter. Because the conspicuous change which is due to the difference of the form about the pore volume equal to or less than 50 nm wasn't found from Fig.3, Fig.4, Fig.5, Fig.6, in the consideration after that, the object was narrowed down to the pores with 50nm - 2 μm diameter.

The influence range (the depth) of permeable forms: It is pointed out by KASAI[4] that the influence range (the depth) where the permeable forms exerts a change on the pore structure of concrete is about 30 mm from the surface of forms[4]. The result which compared the data which is the same as Fig.3, Fig.4 every depth from the surface of forms by every experiment is shown in Fig.5, Fig.6 and Table 3.

In experiment A, the pore volume with 50nm-2μm diameter using a permeable form are decreased more to about 75 % in the 4th layer (the 30 - 50 mm depth from the surface of the test forms) than the plywood forms.

In the same way, in experiment B, 50nm-2μm pore volume decreased more to 61%-76 % in the 3rd layer (30-50mm) than in the plywood forms and they decreased to 56%-67 % in the 4th layer (50-100mm). According to the kind of the permeable forms, the size of the parts and the way of execution, however, It is supposed from these results that the permeable forms exert a change on the pore structure of concrete from the surface to about 30mm-50 mm depth. So, considering the influence range (the depth) where the permeable forms exert a change on the pore structure of concrete surely to examine the correlation of the pore volume and each of the test results such as the neutralization, it was decided to use the data of the pore volume in the 1st layer from concrete surface (the depth depends on the experiment) and the pore volume about the depth of the 0 - 30 mm range from the test form surface.

Repeated use of permeable forms and pore structure: About the repeated use of the permeable forms and the pore structure, considering the result (Fig.3, Fig.4, Fig.6) of experiment B, there is not a big change in total pore volume and 50nm-2μm pore volume from the value of (D0) at the time of first placing at the specimen D2, D4 which used permeable forms repeatedly. Also, as for the influence range of the permeable forms, it is thought that there is not a conspicuous change. According to the kind of the permeable forms, however, it is thought by these results that the change of the pore structure and the influence range don't change too much even if they repeatedly use permeable forms five times (casting concrete five times).

Relationship between the volume of removed excess water and the pore volume: Relationship between the volume of removed excess water and the pore volume is shown in Fig.7 (the 1st layer from concrete surface) and Fig.8 (0 - 30mm layer from concrete surface). The value with volume of removed excess water is the value of the volume of removed excess water of the test forms divided by the form area. In the permeable

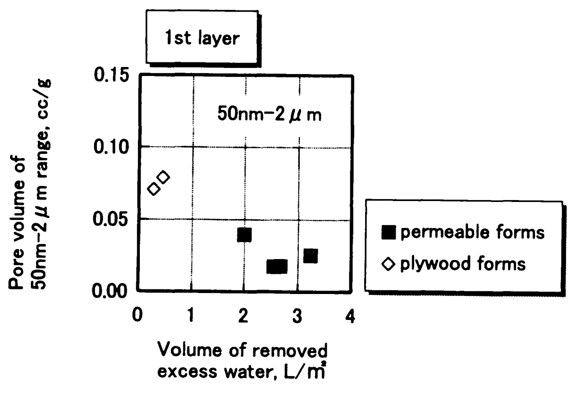

Fig.7 Relationship between volume of removed excess water and pore volume (1st layer from concrete surface)

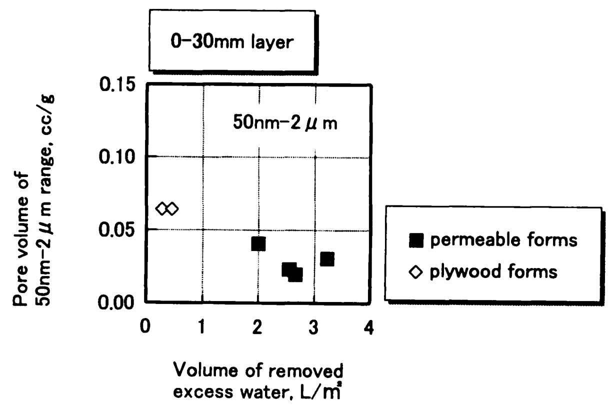

Fig.8 Relationship between volume of removed excess water and pore volume (0- 30mm layer from concrete surface)

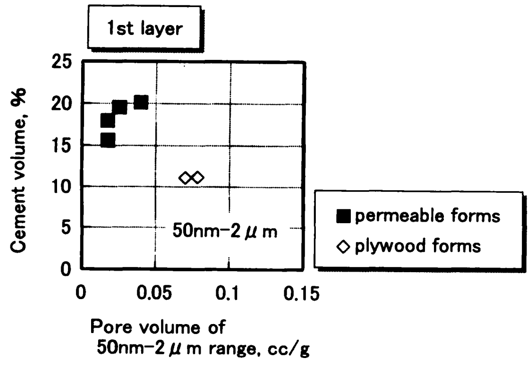

Fig.9 Relationship between pore volume and cement volume (1st layer from concrete surface)

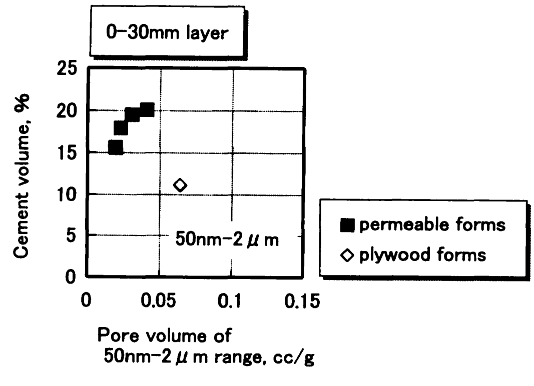

Fig.10 Relationship between pore volume and cement volume (0- 30 mm layer from concrete surface)

forms, 2 ~ 3L/m^2 excess water is drained. The volume of removed excess water was increased by using a permeable forms and with it, 50nm-2μm pore volume tended to decrease. It is possible to say that this shows that the discharge of excess water in concrete changes pore structure.

Relationship between the pore volume and the cement volume: Relationship between the pore volume and the cement volume is shown in Fig.9 (the 1st layer from concrete surface) and Fig.10 (0-30mm layer). The permeable forms have the more cement volume than the plywood forms either in the 1st layer, 0 -30mm layer. It is thought that this shows cement paste to be moving too, with the movement of excess water from inside the form to the surface. As for the relationship between the pore volume and the cement volume, a tendency that using permeable forms increases the pore volume with 50nm-2μm diameter and decrease the cement volume with it both in the 1st layer and the 0-30mm layer is observed.

3.2 Correlation between pore volume and durability

Relationship between pore volume and depth of accelerated neutralization: The relationship between the pore volume and the depth of accelerated neutralization is shown in Fig.11 (1st layer) and Fig.12 (0 - 30mm layer). The tendency that the pore volume with 50nm - 2μm diameter decreases when using permeable forms and that the depth of accelerated neutralization, too, decreases is observed. According to Mehta[13] and Feldman[14], the air permeability of concrete has a deep relationship with the pore volume above a fixed diameter, especially it supposes that there is correlation with the quantity of the coarse capillary pore that the diameter is equal to or more than 100 nm.

In the same way, use of permeable forms decreases the quantity of the coarse capillary pore (it is considered the pore volume of 50nm-2μm) and enhances the efficiency to resist neutralization in this consideration. There is no direct relationship to the pore volume but it shows a relationship between the depth

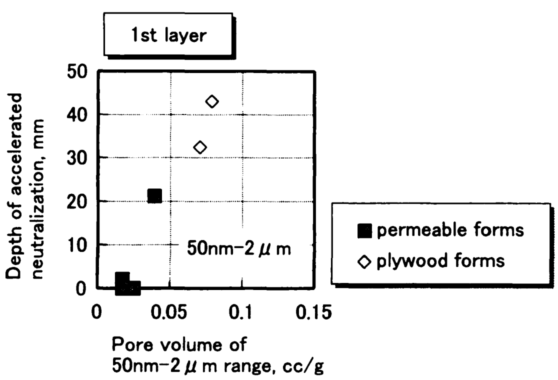

Fig.11 Relationship between pore volume and depth of accelerated neutralization (1st layer from concrete surface)

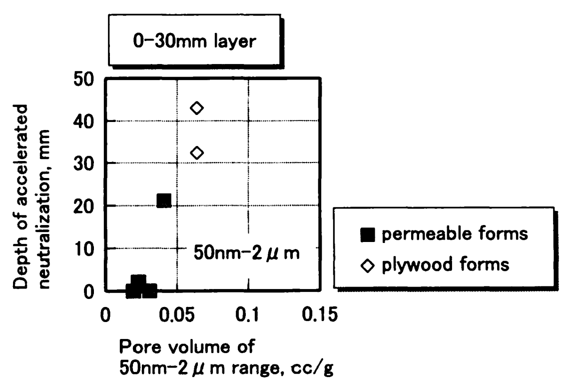

Fig.12 Relationship between pore volume and depth of accelerated neutralization (0- 30mm layer from concrete surface)

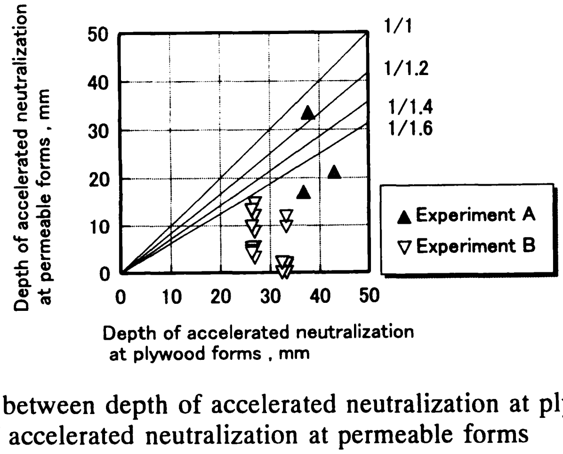

Fig.13 Relationship between depth of accelerated neutralization at plywood forms and depth of accelerated neutralization at permeable forms

of accelerated neutralization about the plywood forms and the depth of accelerated neutralization about the permeable forms in Fig.13 from viewpoints such as the durable improvement which is due to the use of the permeable forms. In this figure, all comparable data in experiment A and experiment B is used. In Japan Concrete Institute " the point of view about the durable design of the reinforced concrete building[15] ", as the quality correction coefficient when using permeable forms for the form, it makes premium coefficient Q_3 = 1.2. As for the data in case of the consideration this time, except for one piece of data which is peculiar, all others are Q_3 = 1.6 it was in above range. It depends on the efficiency and the part, the casting height of the permeable forms and so on, but it is thought that there is possibility to make the value of quality correction coefficient Q_3 to be equal to, or more than 1.2 in value.

Relationship between pore volume and chloride ion penetration amount: According to Uchikawa[16], there is a positive correlation between the equal to or more than 50 nm pore volume of the cement paste, the mortar, concrete and the ion penetrate-ability (the diffusion coefficient of sodium ion). On the other hand, there is a report[17] that the high correlation (the positive correlation) is observed between the pore volume with 10nm-20nm diameter and the chloride ion penetration amount in high-fluid concrete using blast-furnace slag minute powder. Strictly speaking, these experiment handling the chloride ion penetration by *the diffusion are* different from the test of this paper handling the chloride ion penetration by the dry-wet repeating test. However, when considering the relationship between the pore volume and the chloride ion penetration amount, there seems to be a correlation.

Relationship between pore volume and chloride ion penetration amount in this paper is shown in Fig.14 (1st layer) and Fig.15 (0-30mm layer). Here, it is using only the data of experiment B. The pore volume with 50nm-2μm diameter decreases when using permeable forms in the 1st layer but the chloride ion penetration

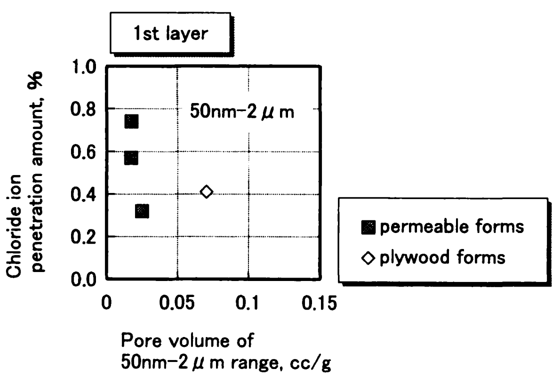

Fig.14 Relationship between pore volume and chloride ion penetration amount (1st layer from concrete surface)

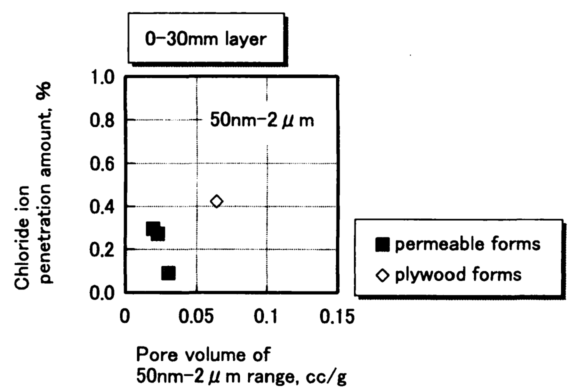

Fig.15 Relationship between pore volume and chloride ion penetration amount (0- 30mm layer from concrete surface)

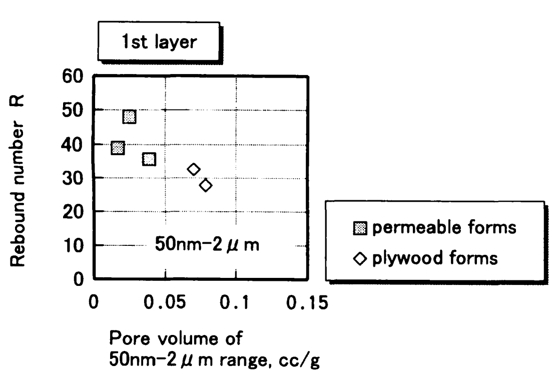

Fig.16 Relationship between pore volume and surface strength (rebound number)

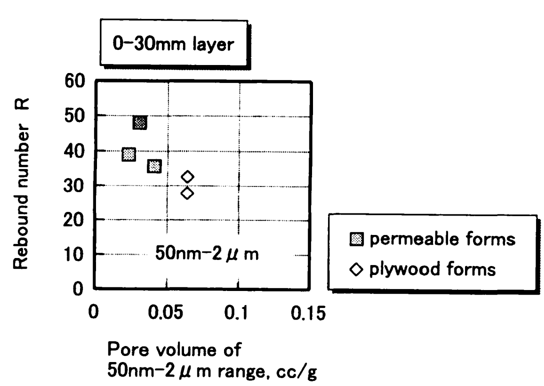

Fig.17 Relationship between pore volume and surface strength (rebound number)

amount rather increases oppositely. However, oppositely in the 0-30mm layer, the pore volume with 50nm-2μm diameter decreases when using permeable forms and with it, the chloride ion penetration amount, too, becomes rather small. This shows that the use of the permeable forms made the surface accurate and that more chloride ion is accumulated only in the concrete surface and that chloride ion penetration inside is restrained. A different tendency was obserbed just at the surface as mentioned above. However, when considering the correlation with the pore volume at about 30mm thickness, the positive correlation between the pore volume of 50nm-2μm diameter and the chloride ion penetration amount was observed as like as Hanehara.

Relationship between pore volume and surface strength (rebound number): Relationship between pore volume and surface strength (rebound number) is shown in Fig.16 (the 1st layer) and Fig.17 (the 0-30mm layer). Generally, using permeable forms increases the surface strength of concrete about 1.5 times as compared to the plywood forms at 4 weeks[3]. About the pore structure and the compressive strength, it is said that the correlation between the compressive strength and the pore volume of 6nm-2μm range is high in cement paste and that the correlation between the compressive strength and the pore volume of 50nm-2μm range is high in mortar and concrete[18]. Also, in this paper, using permeable forms decreases pore volume of 50nm-2μm diameter. And with it, as for the surface strength (the degree of Schmidt hammer of the repulsion), the tendency which becomes about 20 - 30 % bigger at the numerical value with degree of the repulsion was observed.

4. Conclusions

From the test result of pore size distribution, cement volume distribution, accelerated neutralization, chloride ion penetration amount and surface strength by the concrete which used permeable forms or the concrete which used plywood forms, the relationship between the pore structure of concrete, i.e. pore volume and pore size distribution of 6nm- 2μm diameter which is measured in mercury porosity-meter, and the improvement of durability of neutralization, chloride ion penetration and so on and surface strength is considered. As a result, the following could be confirmed.

About the change of pore structure,

1) Use of permeable forms changes the pore structure of concrete and total pore volume decreases conspicuously. It mainly depends on the decrease of pore volume ranging between 50nm and 2μm diameter.
2) The influence range where permeable forms exerts a change on the pore structure of concrete is to 30mm or 50mm depth from the concrete surface.
3) The change of pore structure above-mentioned and the influence range don't have a change too much even if they repeatedly use permeable forms four times (casting five times).
4) Use of permeable forms increases volume of removed excess water, and with it, pore volume of 50nm -2μm tends to decrease.
5) Use of permeable forms decreases pore volume of 50nm - 2μm diameter, and with it, cement volume of concrete tends to increase.

About the relationship between pore volume and the durability,

6) Use of permeable forms decreases pore volume of 50nm -2μm diameter, and with it, the depth of accelerated neutralization tends to become substantially smaller.
7) The surface strength (rebound number of Schmidt hammer) also tends to become rather large.
8) Even if use of permeable forms decreases pore volume of 50nm -2μm diameter, the chloride ion penetration amount increases oppositely in the 1st layer but the chloride ion penetration amount tends to decrease in the 0 - 30mm layer from concrete surface.

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