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OXYGEN TRANSMISSION THROUGH CONCRETE RELATED TO REINFORCEMENT CORROSION

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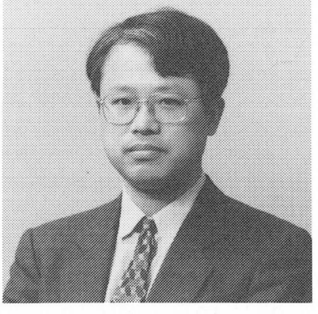

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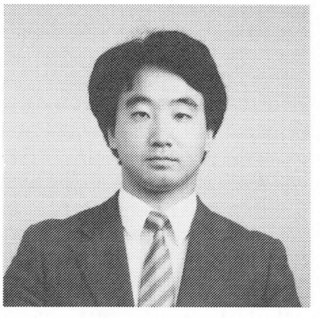

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SYNOPSIS

Oxygen transmission through concrete related to reinforcement corrosion is measured using electro-chemical procedures. Based on the measurement, the influence of cover thickness, curing condition, ambient humidity etc. on the oxygen transmission is discussed. The main conclusions in this paper are summarized as follows. (1) Cover thickness has not always remarkable influence on oxygen transmission related to reinforcement corrosion. (2) The influence of curing condition and ambient humidity is very large.

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1.INTRODUCTION

It has been considered that concrete structures are originally excellent in durability and their lifetime is very long. In recent years, however, there have been increasingly many reports concerning with relatively early deteriorations due to reinforcement corrosion. Reinforcement corrosion is liable to form cracks in covering concrete owing to a volumetric increase caused by corrosive products, resulting in reduced reinforcement areas and subsequently having a considerably adverse effect on the performance of concrete structures.

The process of reinforcement corrosion in concrete may be generally classified as corrosion latent period and corrosion progress period. The liquid phase of pores in concrete around the reinforcement normally has high alkalinity of about pH 13. Under such environment, the reinforcement generally forms a passive oxide film of steel and is therefore hard to corrode. And thus, only the reinforcement surface is oxidized in which the rate of corrosion can be regarded as almost 0. On the other hand, there is a case where not the so-called environment around the structure but the micro environment in the vicinity of the reinforcement changes and the passive oxide film is consequently destroyed. From the standpoint of reinforcement corrosion, the most intrinsic environment is concerned with the neighborhood of the reinforcement because corrosion reaction occurs in the interface between reinforcement and concrete.

If a large amount of chloride ions are present in the concrete or if the concrete is carbonated, the passive oxide film is destroyed, causing the reinforcement to corrode. Therefore, theory-of-equilibrium-like study is needed with regard to the latent period of corrosion, which is defined as the time required until corrosive substances such as carbon dioxide and chloride infiltrate to the surface of reinforcement and their concentration grows enough to cause corrosion. Once the passive oxide film of the reinforcement is destroyed and corrosion occurs, water and oxygen are consumed and corrosion proceeds. This is referred to as corrosion progress period for which speed-theory-like study is mainly required. Since corrosion proceeds electro-chemically, the electric resistance of concrete is an important factor affecting the corrosion during this period.

The supply of oxygen needed for cathode reaction is a principal factor that greatly controls the speed of corrosion being generally considered as the speed control stage of corrosion reaction in concrete. Accordingly, the oxygen transmission through concrete is a very important problem to be made clear in precision of the corrosion speed related closely to the life of concrete structures after occurrence of corrosion in the reinforcement.

Attempts have been done to estimate the oxygen transmission from the penetration of water and chloride ion into concrete. However, as the penetration mechanism of water is different from that of chloride ion, and therefore the correlation between both is not always high [1], it seems difficult to estimate oxygen transmission from the results obtained for other substances. Oxygen transmission relating to corrosion is considered attributable to diffusion. And it is known that from Arenius' formula concerning reaction speed, the logarithm of diffusion coefficient can be expressed by the primary function of the reciprocal of absolute temperature [2]. When corrosive products is formed accumulatively, there is possibility that the diffusion speed decreases owing to a rust layer [3]. Furthermore, it is pointed out [4] that both of water-cement ratio and water content of concrete have significant influence on the oxygen diffusion through concrete.

The authors have already reported about the influence of water-cement ratio and various concrete-surface treatments on the oxygen transmission by using an electro-chemical model including the effect of reinforcement, taking into consideration the fact that corrosion reaction is a phenomenon that occurs in the interface between concrete and reinforcement [5]. With regard to curing condition, ambient humidity, etc., the authors have also pointed out that there is possibility that the influence of environmental condition is greater than that of cover thickness [6], but no complete evaluation has been made in this respect.

The object of the present research is to obtain fundamental data for establishing the rational durability design of concrete structures, by examining experimentally and analytically the effect of cover thickness, curing condition and ambient humidity as well as concrete surface treatments on the oxygen transmission through concrete.

2. OUTLINE OF OXYGEN TRANSMISSION TEST

(1) Test methods

In accordance with the methods described in Bibliography [5], the oxygen diffusion rate and oxygen diffusion coefficient were determined by installing steel plate or reinforcing bar in concrete and by measuring electro-chemically the maximum amount of oxygen in steady state that can reach the steel surface from the concrete surface.

(2) Test variables

The test variables chosen in the present research are as follows:

a) Concrete mix

Based on the concrete mix prescribed in "Standard Specification on Concrete <Execution of Work> Chapter 20 - Marine Concrete" established in 1986 by the Japan Society of Civil Engineers, the following conditions were selected for design of mix proportion: slump: 8 ± 1 cm; air content: about 4%; water-cement ratio: 50%; unit cement content: 360 kg/m^3, in which high-early-strength Portland cement was used. The specified mix of concrete is shown in Table 1.

b) Concrete cover

Three kinds of cover thickness, i.e., 30, 50 and 70 mm, were chosen with reference to "Standard Specification on Concrete <Design> Chapter 10 - General

Table 1 Mix proportion of concrete

W/C (%)	Slump (cm)	Air content (%)	s/a (%)	Maximum size of coarse aggregate (mm)	Unit content (kg/m³)				Admixture (AE water reducing agent) (g/m³)
					Cement	Water	Fine aggregate	Coarse aggregate	
50	8±1	4±1	55	15	360	180	942	799	1800

Structural Details 10.2 Concrete Cover".

c) Curing condition

The standard specimens were sealed in the vinyl bag for 3 days with reference to the wet curing of high-early-strength Portland cement concrete prescribed in "Standard Specification on Concrete <Execution of Work> Chapter 8 - Curing of Concrete". In addition, to examine the influence of curing condition on oxygen transmission through concrete, from removal was made at the age of 1 day after sealed curing, and water curing (temperature: 20 ± 1 ℃) or air curing (temperature: 20 ± 1 ℃; humidity: R.H. 85 ± 5 %) was done up to an age of 3 days. After these three kinds of initial curing, all the specimens were placed in the constant temperature and humidity room (20 ± 1 ℃, R.H. 85 ± 5 %) until tested at the age of about 6 weeks.

d) Ambient humidity condition

In order to examine the influence of ambient humidity on the oxygen diffusion through concrete, the following three conditions were chosen as relative humidity at a constant temperature of 20 ± 1 ℃: R.H. 85 ± 5 %, R.H. 60 ± 5 % and under water. Meanwhile, ambient humidity is R.H. 85 ± 5 % in cases unless otherwise specified.

e) Direction of bar arrangement

There is possibility that owing to bleeding and settlement the properties of concrete near the reinforcement differs between the case where the main reinforcement is arranged horizontally like beam and slab and the case where it is done vertically like column. To examine this, two types of bar arrangement, horizontal and vertical directions, were chosen. At the same time, two examine the difference of the oxygen carry-over rate between two opposite surfaces of a reinforcing bar far and near the concrete surface, the bar was cut in half along the axial direction, and the oxygen carry-over rate was measured on each corresponding surface.

f) Height of member

In the relatively tall members such as column, there is difference occurring in the quality of concrete between its upper part and lower part [7]. In this research, with reference to the requirement that the height of 1 layer shall be 40 to 50 cm or less as specified in "Standard Specification on Concrete <Execution of Work> Chapter 7 - Transport and Placing", the concrete was placed up to a height of 120 cm at a time, which is 3 times as much as specified height 40 cm. After hardening it was cut into 3 parts of about 40 cm each using a concrete cutter and the variation in oxygen transmission owing to the position in the member-height direction was examined.

g) Reinforcement spacing

To examine whether or not the amount of oxygen that reaches the reinforcement surface can be affected by the reinforcement spacing in concrete, three kinds of the spacing, i.e., 10, 10/2 = 5, 10/3 = 3.3 cm, were selected with reference to the requirements that the horizontal reinforcement spacing in beam shall be more than 2 cm, more than 4/3 times as much as the maximum size of coarse aggregate (20 mm here) and more than the diameter of reinforcement (16 mm here); whilst in column shall be more than 4 cm, more than 4/3 times as much as the maximum size of coarse aggregate (20 mm here) and more than 1.5 times as much as the diameter of reinforcement (24 mm here), specified in "Standard Specification on Concrete <Design> Chapter 10 - General Structural Details.

h) Concrete surface treatment

In the same way as Bibliography [5], three types of surface treatment material were used, that is, material based on bisphenol A epoxy resin (abbreviation: epoxy) which is practically used at present, material based on poly-buthadiene urethane resin (abbreviation: urethane) which is excellent in crack bridging performance, and material in which polymer cement mortar is applied after silan oligomer with water repellency is impregnated (abbreviation: silan + PCM).

In accordance with "Guide to protection of road bridges against damage from salt (draft) and its commentary" and the practical repair work, the lining film thickness (amount of application) was set as follows: for epoxy and urethane, 240 μm; for silan + PCM, silan 130 g/m^2 and PCM 1.2 mm. Elongation capacity which is an important property in repair working was 50% for epoxy and 400% for urethane.

The film thickness of epoxy and urethane was controlled by their application weight and then adjusted with a wet gauge measurement.

(3) Test specimens

a) Types of specimens

Two series of specimens were prepared, i.e., one uses the steel plate as working electrode which is intended to examine the diffusion of oxygen through concrete using a one-dimensional simplified model (steel-plate series) and another uses the reinforcing bar (reinforcement series).

i) Steel-plate series

In this series, cover thickness, curing condition, ambient humidity and surface treatment specification were chosen as test variables, and two specimens were prepared for each variable.

As shown in Fig.1, the steel plate was installed as working electrode in the bottom of a vinyl chloride container having inside diameter of 20 cm. A conducting wire from the steel plate was let out of the container, and then concrete corresponding to cover thickness of 3, 5 and 7 cm was placed on it and compacted using a vibrator. As counter electrode, a reticulated steel wire was embedded. A platinum wire was used as reference electrode whose potential stability was checked by preliminary test.

The steel plate was bonded to the bottom of the container by use of epoxy resin, and immediately before casting concrete the same resin was also applied to the inside wall of the container to prevent the penetration of water and air from aperture between the concrete and the container. The upper surface of the specimen was cleaned well before the surface treatment was applied.

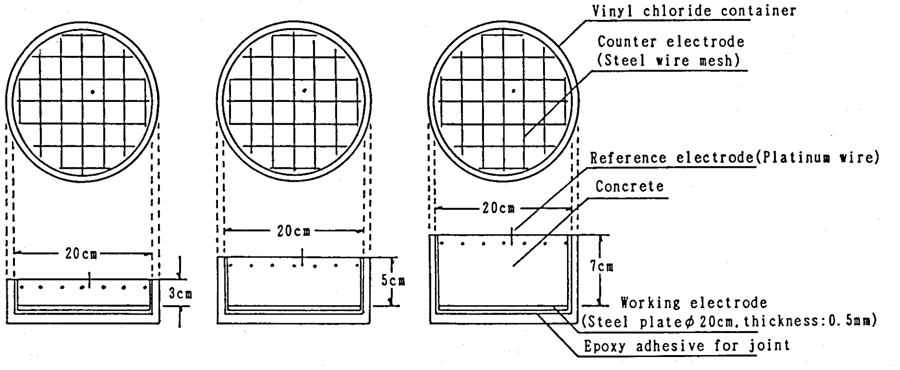


Fig. 1 Specimen for steel-plate series

ii) Reinforcement series

In this series, cover thickness, type of reinforcement, reinforcement spacing, direction of reinforcement arrangement and height of member were chosen as test variables, and each two specimens were prepared.

For the horizontal-reinforcement, the specified number of reinforcement was embedded at the determined cover thickness (3, 5 and 7 cm) as working electrode in the prism specimen of 10 × 10 × 40 cm as shown in Fig.2. In addition, the same number of the reinforcements as working electrode was arranged for counter electrode, and a conducting wire was let out of each reinforcement. As reference electrode, a platinum wire was used in the same way as the steel-plate series. The five sides (excluding the concrete-placing surface) of each specimen were lined with epoxy resin of more than 10 mm in film thickness at the age of about 7 days, to prevent the intrusion of oxygen.

On the other hand, for the vertical-reinforcement, two different types of specimen of 10 × 10 × 120 cm and 10 × 10 × 40 cm were prepared, in which the working electrode and counter electrode were arranged in the same way as the horizontal-reinforcement. A platinum wire was used as reference electrode. The specimen having a height of 120 cm, was cut into 3 pieces of each 40 cm by means of a concrete cutter at the age of about 10 days, and the sides excluding one side corresponding to the concrete-placing surface of the horizontal reinforcement specimen were sealed with epoxy resin.

Deformed bar (D13 SD35) was used as standard reinforcement. To observe comparatively the effect of the black skin and reinforcement sectional configuration, the specimen using a polished round bar (φ 13 mm) was also prepared for a case of cover thickness of 5 cm. Also, to examine the carry-over distribution of oxygen to the reinforcement surface, the reinforcement insulated and bonded with epoxy resin after cut half in the axial direction was used as the working electrode.

(4) Test method

To determine the potential which exhibits an oxygen diffusion control phenomenon, polarization test was conducted between -200 mV and -2,000 mV at a scanning speed of -0.08 mV/s using an automatic polarization system. With reference to the report [8] by Gjørv et al., potential E_1 at a critical current density was determined from the polarization curve, and this polarization potential E_1 was given to the sample electrode of the specimen by the use of a

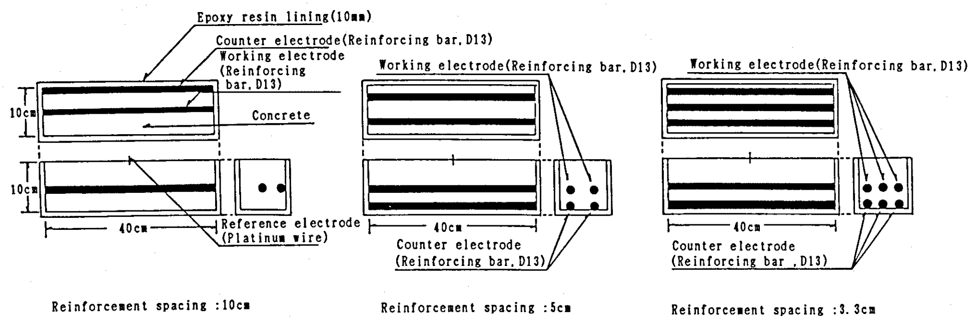


Fig. 2 Specimen for reinforcement series

potentiostat.

Meanwhile, for underwater test, air was continuously blown into the water through an air pump so that the concentration of oxygen in the water is kept constant.

A resistance-free ammeter was used to measure the current between the counter electrode and the potentiostat. Measurement was performed at intervals of 24 hours until 8 to 15 days later when the current converges to an almost constant value after starting polarization. Using this final current, in the same way as described in Bibliography [5], oxygen diffusion rate J which is the amount of oxygen that reaches the unit surface area of the reinforcement per the unit time and apparent oxygen diffusion coefficient D based on the assumptions that the diffusion distance is regarded as cover thickness and also the coefficient D is uniformly distributed were calculated.

3. TEST RESULTS AND DISCUSSIONS

Although some results showed large scatters, discussions were done using the average of measured values for each two specimens as described below.

Both steel-plate series and reinforcement series showed a tendency in which the current converges to a constant value 7 to 12 days later. In the steel-plate series, the amount of current increased with the lapse of time. In the reinforcement series, on the other hand, many of specimens shows a tendency of converging with a decrease in current. This is considered mainly attributable to the fact that the distribution of initial concentration of oxygen varies with the distribution of pores in concrete as well as with the distribution of moisture content according to numerical analysis. The latter tendency may possibly be caused by many pores present near the reinforcement surface because of its shape.

(1) Steel-plate series

a) Considerations by test results

The influence of cover thickness on oxygen diffusion rate J under various surface treatment specifications is illustrated in Fig.3. Also, the influence of cover thickness on J under each curing condition is shown in Fig.4.

It was anticipated that the larger the cover thickness the smaller become both

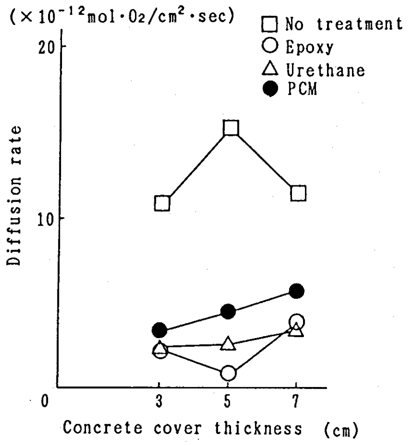


Fig. 3 Influence of cover thickness on oxygen diffusion rate J under various surface treatment specifications

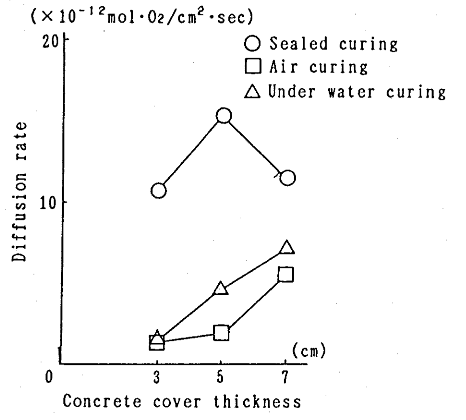


Fig. 4 Influence of cover thickness on oxygen diffusion rate J under each curing condition

of concentration gradient of oxygen and oxygen diffusion rate J. However, diffusion rate J does not always become small even if the cover thickness increases and rather has a tendency to decrease. These result agree with those reported previously by the authors [6], and can be considered mainly attributable to the fact that oxygen relating to corrosion reaction is not simple gaseous oxygen but dissolved oxygen which exists in the liquid phase of pores. Accordingly, it can not be expected that at the water-cement ratio (50%) under environmental conditions adopted in this test, the transmission of oxygen through concrete is restricted well by the increased cover thickness. Meanwhile, the report of the underwater tests by Gjørv et al. indicated that the oxygen diffusion rate decreases somewhat with increase in the cover thickness. On the other hand, the surface treated specimens showed a smaller value of J than those without treatment, and the effectiveness in insulating oxygen can be recognized remarkably in epoxy and urethane in particular.

Curing condition has a significant influence on oxygen transmission. The value of J is smallest in air curing, followed by water curing and sealed curing. The reason for the smallest oxygen diffusion rate in air curing may be due to that a thin film of calcium carbonate was formed on the concrete surface in the air, resulting in insulation of the oxygen by the same effect as surface treatment. Also, the water curing can be considered to make the diffusion rate considerably small because of the reduced capillary pores in concrete.

The influence of ambient humidity on oxygen diffusion rate J is shown in Fig.5. The value of J under both of water and R.H. 60% environment was considerably smaller than that under R.H. 85%. In addition, the relation between the moisture content in concrete and the diffusion rate is shown in Fig.6, in which the moisture content was calculated by the following equation :

$$\text{Moisture content} = 100(W-W_D)/(W_S-W_D)\,(\%) \qquad (1)$$

Where, W : weight of concrete immediately after the end of test
W_S : weight of concrete saturated in water after the end of test
W_D : weight of concrete dried until a constant weight is obtained

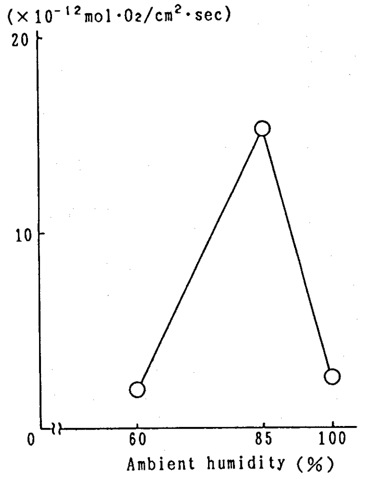


Fig. 5 Influence of ambient humidity on oxygen diffusion rate J

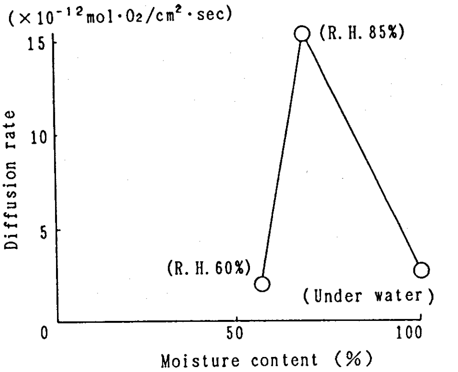


Fig. 6 Relation between the moisture content in concrete and the diffusion rate

under oven condition at 105°C.

According to Fig. 6, the specimen under water as compared with R.H. 85% shows a small diffusion rate. On the other hand, the diffusion rate at R.H. 60% where the moisture content is lowest, is rather smaller than that at R.H. 85%. As the carbonation of concrete proceeds rapidly at R.H. 60%〔9〕, there is a high possibility that the calcium carbonate produced in pores decreased the transmission of oxygen. However, if the period of test becomes long and the moisture content in concrete becomes small, the electric resistance of concrete increases and hence the polarization is possibly spent in the ohmic decline of concrete. These are the problems to be further studied.

The apparent diffusion coefficient D is shown in Table 2. It is found that the value of D tends to increase as cover thickness increases and to increase in the following order in the same way as diffusion rate J : epoxy < urethane < silan + PCM < without lining. Regarding the influence of curing condition, also, the same tendency as found in J was observed. The value of D becomes high in the order of R.H. 60%, 85% and under water with respect to the environmental condition, resulting in somewhat different tendency from the case of J. This is considered attributable to the influence of surface concentration as described later.

b) Consideration by numerical calculation on the influence of cover thickness

According to test results, the oxygen diffusion rate dose not change so much even if the cover thickness is increased. Moreover, it was recognized that apparent diffusion coefficient D becomes large as the cover thickness increases. It can be considered that if the paste layer produced on the covering concrete surface is fully dense, the influence of cover thickness on oxygen transmission will be small. In the case where concrete is placed in the air, however, the dense layer is not always formed on the surface〔4〕. In general, the diffusion of oxygen in concrete may be broadly divided into two types as gaseous oxygen in pores and dissolved oxygen in porous water. It is known that of the latter, and that the diffusion coefficient differs by 10^4 to 10^5 approximately〔10〕.

Table 2 Apparent oxygen diffusion coefficient D

(a) Influence of surface treatment specification ($\times 10^{-6} cm^2/sec$)

Cncrete cover(cm)	3	5	7
No treatment	3.59	8.57	9.01
Epoxy	0.74	0.44	2.94
Urethane	0.84	1.45	2.72
Silan+PCM	1.13	2.49	4.49

(b) Influence of curing condition

Sealed curing	3.59	8.57	9.01
Air curing	0.53	1.12	4.31
Water curing	0.48	2.64	5.65

(c) Influence of ambient humidity

R.H. 60%	—	1.11	—
R.H. 85%	—	8.57	—
Under water	—	53.2	—

Pores in concrete are not distributed uniformly. Relatively many pores exist in concrete near the top surface owing to bleeding and the number of pores decreases gradually far from the surface. Especial, when the paste is forming a dense layer on the reinforcement surface, there is high possibility that the layer with less pores exists in the vicinity of the interface between concrete and reinforcement. Measurement of the pore distribution of less than 0.004 mm in radius indicated explicitly that a total volume of the pores contained in the unit concrete volume is about 50 to 70 % larger in the neighborhood of the covering surface as compared with the neighborhood of the reinforcement.The value of such fine pores in the latter scarcely varied with the cover thickness. Also, it should be noted that micro cracks are likely to occur owing to drying shrinkage, etc. near the covering surface and that the oxygen diffusion speed becomes extremely high once the cracks develop〔11〕. On the other hand, the moisture content in pores is low at the covering surface owing to dissipation of moisture from concrete and becomes high toward the inside.

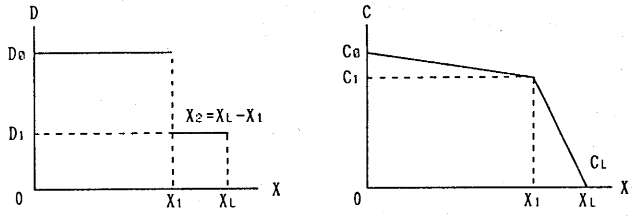
As a result, the oxygen in concrete can be considered to reach the reinforcement surface through a complicated route composed of gaseous and liquid phases. Therefore, it is very difficult to model this phenomenon accurately. For the purpose of quantitatively determining the transmission of oxygen it is more practical to carry out macroscopic treatment on the assumption that the diffusion coefficient D is expressed by a certain distribution relating to the distance from the concrete surface.

Since the volume of pores is relatively large and the moisture content is low near the surface of the covering concrete, the diffusion in the gaseous phase occurs at a larger extent than that in the liquid phase and thus the value of D becomes large. On the contrary, the porosity decrease and the moisture content increases toward the inside, resulting in the smaller value of D.

On the other hand, when treating the migration of substance as diffusion phenomenon, an important matter is surface concentration. For example, Ohshiro et al.〔12〕 conducted experimental and analytical studies on the diffusion of chloride ion into concrete and found that the surface concentration of chloride varies with the quality of concrete and gives a large influence on the diffusion.

Therefore, when studying the diffusion of oxygen strictly, it is necessary to take into account the surface concentration of oxygen together with the distribution of porosity and moisture content. when the specimen after tested at ambient humidity of R.H. 85 % was allowed to place in water, the volumetric adsorption of concrete at a steady state was about 10 %. Assuming that the total volume of the gaseous phase relating to the diffusion of oxygen through concrete corresponds to this adsorption and also this is distributed uniformly, the surface oxygen concentration in concrete is only about 1/10 of that in the air. The above mentioned calculation of D was conducted on the assumption that D is uniform throughout the concrete, taking no special consideration to the surface concentration of oxygen. Nextly, some discussions are done by numerical calculation when distribution of D is not uniform.

(1) Study on the assumption that D is distributed stepwise on 2 levels



Distribution of oxygen diffusion coefficient D

Distribution of oxygen concentration C

Fig. 7 Distribution of oxygen diffusion coefficient in (1)

If D is distributed as shown in FIg. 7, diffusion rate J can be expressed as follows:

At $0 \leqq x \leqq x_1$,

$$J = -D_0 (C_1 - C_0)/x_1 \qquad (2)$$

At $x_1 \leqq x \leqq x_L$,

$$J = -D_1 (C_L - C_1)/x_2 \qquad (3)$$

Here, x is a depth from the concrete surface; x_0, concrete surface; x_L, reinforcement surface. Also, C is the oxygen concentration, and oxygen concentration C_L on the reinforcement surface is assumed to be 0 from the phenomenon of diffusion speed control in the corrosion process.

From equations (2) and (3), D_1 can be obtained by the following equation:

$$D_1 = Jx_2 / \{C_0 - J(x_L - X_2)/D_0\} \qquad (4)$$

Where, with reference to measurement on plain concrete by Kobayashi et al. [3], Do was assumed to be $3.2 \cdot 10^{-3}$ (cm^2/s) for concrete mix proportion and curing condition of tested specimens, and then oxygen concentration in the air is assumed to be $C_0 = 8.9 \cdot 10^{-6}$ ($mol \cdot O_2/cm^3$).

Furthermore, cover thickness: $x_L = 5.0$ (cm), steel-plate surface concentration: $C_L = 0.0$ ($mol \cdot O_2/cm^3$), and from experimental values measured herein, diffusion rate was assumed to be $J = 150 \cdot 10^{-13}$ ($mol \cdot O_2/cm^2/s$). In calculation of D_1, the

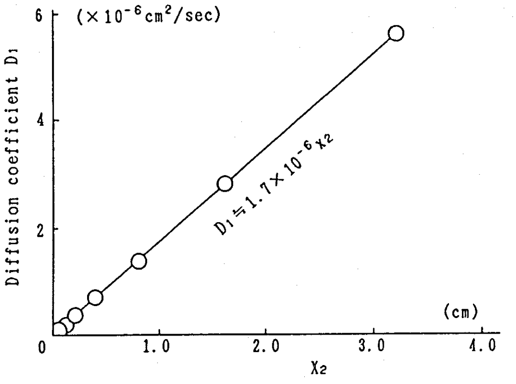


Fig. 8 Relationship between x_2 and D1

values of x_2 were changed as 0.00, 0.05, 0.10, 0.20, 0.40, 0.80, 1.6 and 3.2 (cm). Results of calculation from equation (4) are shown in Fig. 8.

x_2 and D_1 are almost in proportional relationship. This is because $C_o \gg J(x^L - X_2)/D_o$ in equation (4), hence it can be approximated as follows:

$$D_1 \doteqdot JX_2/C_0 = 1.7 \cdot 10^{-6} \cdot X_2 \qquad (5)$$

Assuming that the pore structure is uniform throughout the concrete, the moisture content is 0% on the concrete surface and all pores on the interface with the steel plate are filled with water, then it can be considered that difference between the diffusion coefficients on the concrete surface and on the interface with the steel plate is to be about 10^4 to 10^5 similarly as difference in air and water. As the measured pore structure was not uniform throughout the covering concrete, this difference is possibly larger. Here, it is assumed that the value D is different by about 10^4 to 10^5, since all of pores on the interface with the steel plate are not always filled with water. Even if the effect due to surface oxygen concentration is taken into account, it can be considered that the thickness of the layer having a considerably small. D value near the steel plate is at most less than 0.05 cm as shown in Fig. 8. The maximum thickness of the diffusion layer in the solution was found to be about 0.05 cm〔13〕, Therefore, the thickness of the layer which practically gives a significant influence on the diffusion might be less than 0.05 cm though the diffusion through concrete can be larger than that in solution. Also, according to the calculations for two cases with cover thicknesses of 3 and 7 cm, diffusion rate J is similarly about $150 \cdot 10^{-13}$ and thus the influence of cover thickness on the value of J is extremely small.

(2) Study on the case where a constant layer with small D exists in the neighborhood of the steel plate and D is linearly distributed in other zones

When D is distributed as shown in Fig. 9: at $0 \leqq x \leqq x_1$, it can be expressed as follows:

$$D(x) = (D_1 - D_0)x/x_1 + D_0 \qquad (6)$$

On the other hand, if "Fick's First Law" is transformed, then the following equation can be obtained:

$$dC(x)/dx = -J/D(x) \qquad (7)$$

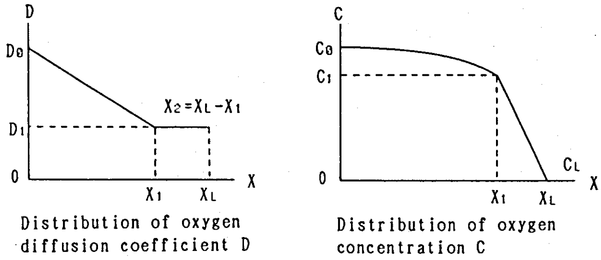


Fig. 9 Distribution of oxygen diffusion coefficient in (2)

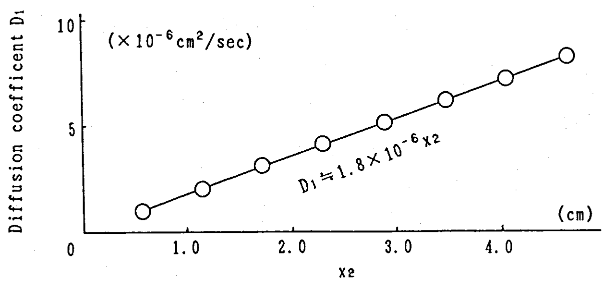


Fig. 10 Relationship between diffusion coefficient D_1 and x_2

Substituting equation (6) into equation (7) and integrating both sides, then

$$C(x) = -(J/A)\ln(Ax+D_0)+K \qquad (8)$$

Where, $A = (D_1-D_0)/x_1$
K : integral constant

Determining the integral constant from $C(x_1)= C_1$ and arranging this, then

$$C(x) = C_1+(J/A)\ln D_1-\ln(Ax+D_0) \qquad (9)$$

Also, from $C(0)=C_0$

$$C(0) = C_1+(J/A)(\ln D_1-\ln D_0) \qquad (10)$$

At $x_1 \leqq x \leqq x_L$,

$$J = D_1(C_1/x_2) \qquad (11)$$

Eliminating C_1 from equations (10) and (11) and substituting $x_1 + x_2 = x_L$, then the following equation can be obtained:

$$x_2 = \{C_0 D_1(D_1-D_0)-Jx_L D_1 \ln(D_1/D_0)\}/\{J(D_1-D_0)-JD_1\ln(D_1/D_0)\} \qquad (12)$$

Where, D_0, C_0, x_L and J are assumed in the same as (a), then x_2 becomes the function of D_1. From equation (12), the relation between D_1 and x_2 was calculated. As shown in Fig. 10, the relationship between D_1 and x_2 is almost linear and can be approximated by next equation, thus showing almost the same as (1).

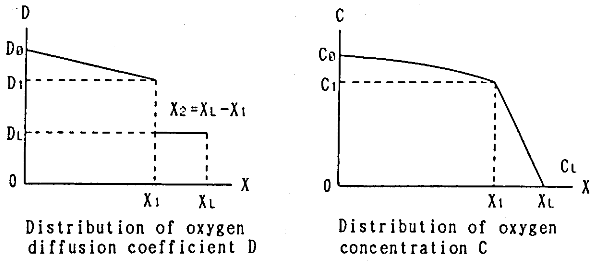


Fig. 11 Distribution of oxygen diffusion coefficient in (3)

Table 3 The calculated results of D_L for various D_1 values in (3)

($\times 10^{-8}$ mol · O_2 · cm^2/s)

b \ a	1	2	3	4	5	6	7	8	9
10^{-8}	8.86	8.85	8.84	8.83	8.83	8.82	8.82	8.81	8.81
10^{-7}	8.81	8.79	8.78	8.78	8.77	8.77	8.76	8.76	8.76
10^{-6}	8.75	8.74	8.73	8.72	8.72	8.71	8.71	8.71	8.70
10^{-5}	8.70	8.68	8.68	8.67	8.66	8.66	8.66	8.65	8.65
10^{-4}	8.65	8.63	8.63	8.62	8.62	8.61	8.61	8.61	8.61
10^{-3}	8.61	8.60	8.59	8.59	8.58	8.58	8.58	8.58	8.58

$D_1 = a \cdot b$

$$D_1 \fallingdotseq 1.8 \cdot 10^{-6} \cdot x_2 \quad (13)$$

(3) Study on the case where a constant layer with small D exists in the neighborhood of the steel plate and D is distributed discontinuously

When D is distributed as shown in Fig. 11, at $0 \leqq x \leqq x_1$, it is the same as (2), hence equation (10) holds. At $x_1 \leqq x \leqq x_L$, the following equation is obtained:

$$J = D_L (C_1 / x_2) \quad (14)$$

Eliminating C_1 from equations (10) and (14) and substituting $x_1 + X_2 = X_L$, then the following equation can be obtained:

$$D_L = Jx_2 (D_1 - D_0) / \{C_0 (D_1 - D_0) - (x_L - x_2) J \ln(D_1 / D_0)\} \quad (15)$$

Here, D_0, C_0, x_L and J are assumed in the same way as (1), then

$$x_2 = 0.05 \text{ (cm)}$$

Thus, D_L becomes the function of D_1. The calculated results of D_L for various D_1 values are shown in Table 3. Even if D_1 is varied widely from 9.0×10^{-8} to 3.0×10^{-3} (mol · O_2 cm^2 /s), D_L changes only in the range of $(8.57 \text{ to } 8.98) \times 10^{-8}$ (mol · O_2 cm^2 /s).

Summarizing these results, it can be considered that the oxygen diffusion rate J scarcely decrease even if the cover thickness is increased since an obstacle layer with a very small oxygen diffusion exists near the interface between concrete and steel plate, by which the diffusion speed is controlled. This may correspond to a state in which moisture still remains in the region near the

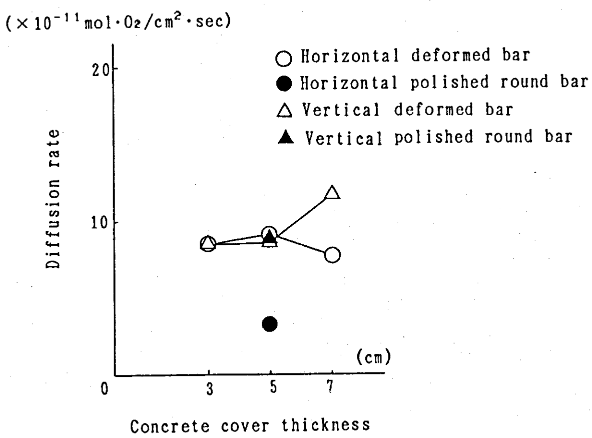


Fig. 12 Influence of cover thickness on diffusion rate

reinforcement even after the moisture near the concrete surface dissipated. Accordingly, when taking into account the oxygen transmission through concrete as one factor in the durability design concerning reinforcement corrosion, there is possibility of overestimating the effect of cover thickness if the diffusion coefficient is used, hence it may be desirable to use the diffusion rate as index. Meanwhile, the existence of this obstacle layer can result in the small diffusion coefficient compared to that given by the equi-pressure method. [5]

(2) Reinforcement series

a) Considerations by test results

In the case of a deformed round bar with black skin, it is possible that corrosive defects are liable to occur on the surface owing to its surface configuration and also that the measured current, because of reduction of black skin (mill scale) and other effects, does not always agree with the diffusion rate of oxygen itself. Accordingly, qualitative studies are mainly conducted herein.

The influence of cover thickness and bar-arrangement direction on the oxygen diffusion rate J is shown in Fig. 12. Irrespective of the bar-arrangement direction, no remarkable influence of cover thickness is recognized similarly as obtained by the steel-plate model. However, the oxygen diffusion rate in the specimen using the deformed round bar is larger than that obtained by the steel-plate model. This may be attributed to not only the existence of defects resulting from the shape of reinforcement but also the possibility due to the results caused by the reaction other than oxygen reducing reaction as cathode reaction. On the contrary, with the horizontal reinforcement using a polished round bar, the diffusion rate is found to be similar to that obtained by the steel-plate model. Since the deformed round bar with black skin is generally used as reinforcement in the actual structures, it may be difficult to measure accurately the oxygen diffusion rate by applying this method. As for the bar-arrangement direction, no remarkable difference is recognized.

The influence of reinforcement spacings on J is show in Fig. 13. In the horizontal bar-arrangement direction, the oxygen diffusion rate J tends to decrease with reducing reinforcement spacing. In the vertical direction, on the

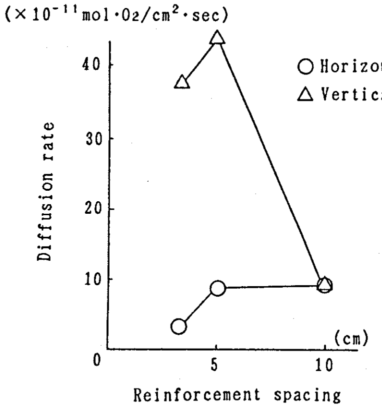


Fig. 13 Influence of reinforcement spacing on diffusion rate

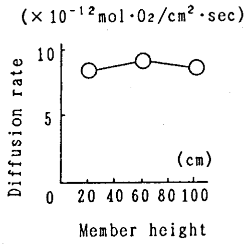


Fig. 14 Influence of member height on diffusion rate

Table 4 Distribution of the amount of oxygen diffused to reinforcement surface

		Near the concrete surface	Far from the concrete surface
Direction of bar arrengement	Horizontal	509	546
	Vertical	704	732

contrary, the value of J with reinforcement spacing of 10/2 or 10/3 cm is rather larger than that with 10 cm. And thus, no explicit relationship was found between the J value and the reinforcement spacing.

For oxygen which is transmitted to reinforcement from concrete surface, there is possibility that its carry-over rate is different between two opposite surfaces of reinforcement near and far from the concrete surface. As shown in Table 4, however, no clear difference is recognized between both, as far as these tests are concerned.

The influence of the member height on J is shown in Fig. 14. Within this test range, no remarkable influence of the member height is observed.

b) Study by numerical calculation of the distribution of oxygen carry-over rate

Using a two-dimensional diffusion model, the distribution properties of oxygen carry-over rate are examined by numerical calculation.

(1) Model

As shown in Fig. 15, the model which allows the oxygen to permeate into the reinforced concrete member from both sides was adopted. The reinforcement sec section was assumed to be square for convenience.

(2) Approximation

The following two-dimensional diffusion equation was solved applying the differential approximation as expressed by equation (17):

$$dC/dt = D(d^2C/dx^2) + D(d^2C/dy^2) \qquad (16)$$

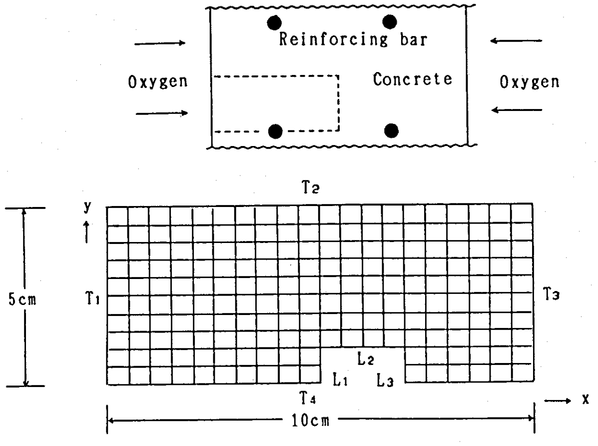


Fig. 15 Two-dimensional diffusion model

$$C(x, y, t+k) = A\{C(x+h, y, t)+C(x-h, y, t)+C(x, y+h, t) +C(x, y-h, t)\} +(1-4A)C(x, y, t) \quad (17)$$

Where, $A = DK/h^2$
$C(x, y, t)$: concentration on point (x, y) at time t
h : interval of distance (x, y ; same) (= 0.5 cm)
k : interval of time (= 10 s)

(3) Calculation of diffusion rate J

Calculation of diffusion rate J on each face of the reinforcement was made as shown below, taking into consideration the concentration gradient near the face only in the x direction with respect to faces L_1 and L_3 and the concentration gradient only in the y direction with respect to face L_2.

With respect to face L_1,

$$J_{L1}(x_{L1}, y_{L1}, t) = -D\{C(x_{L1}-h, t)-C(x_{L1}, t)\}/h \quad (18)$$

With respect to face L_2,

$$J_{L2}(x_{L2}, y_{L2}, t) = -D\{C(y_{L2}-h, t)-C(y_{L2}, t)\}/h \quad (19)$$

With respect to face L_3,

$$J_{L3}(x_{L3}, y_{L3}, t) = -D\{C(x_{L3}-h, t)-C(x_{L3}, t)\}/h \quad (20)$$

Where, x_L, y_L : position of each face, x and y

(4) Initial condition

The initial concentration of oxygen was assumed to be uniform in concrete, being the same as oxygen concentration in the air.

$$C(x, y, 0) = C_o \ (=8.93\times 10^{-6} \ mol \cdot O_2/cm^3)$$

(5) Boundary condition

At boundary T_1, oxygen concentration in concrete was assumed to be always the same as that in the air, at T_2, T_3, and T_4, it was assumed that no oxygen flows in and out because the model is geometrically symmetrical. Also, at L_1, L_2 and L_3, oxygen concentration was set to be zero assuming that the oxygen which has reached is all consumed.

(6) Diffusion coefficient

The test results using the steel plate implied that diffusion coefficient D might not be distributed uniformly, there being a layer with small D in the neighborhood of the reinforcement. Here, for the purpose of comparison, the following two cases were treated, that is, 1)the case where D is distributed uniformly and 2)the case where there is a layer with small D in the neighborhood of the reinforcement.

1)First case:

The same diffusion coefficient D as the steel-plate series was adopted as follows, assuming that concrete is very dry,

$$D = D_0 (=3.2 \times 10^{-3}\ cm^2/s)$$

Diffusion rate J rapidly converged with the lapse of time and reached a constant value 1 day later. The diffusion rates on faces L_1, L_2 and L_3 were proportioned approximately as follows :

$$J_{L1} : J_{L2} : J_{L3} = 5 : 2 : 1$$

2)Second case:

With reference to the value ($8.5 \cdot 10^{-7}$ cm^2/s) for x = 0.5 in equation (3), diffusion coefficient D in the neighborhood of the reinforcement (thickness around the reinforcement surface: 0.5 cm) was selected as $D = D_1$ (= 3.2×10^{-8} cm^2/s), taking into consideration that the diffusion coefficient of oxygen under water and in the air is markedly different in the order of about 10^5. The coefficient D in other parts was assumed to be D_0 similarly as 1).

The value of J showed a tendency of decreasing gradually with of-time and did not converge even after 4 weeks. Also, it is noted that the value of J is almost the same on each face of the reinforcement.

The results obtained in 1) and 2) are summarized in Fig. 16. According to the analytical results obtained in 1), the diffusion rate is clearly different between two opposite surfaces of reinforcement near and far from the concrete surface. In the test results, however, this difference is not clearly observed. If D value around the reinforcement is actually small as assumed in 2) and then its layer thickness is large, the time required for converging of J will be considerably long. Accordingly, although the value of J in the test results seems to converge, there is also possibility that it is not in the real steady state.

4. CONCLUSIONS

In the present research, the oxygen transmission through concrete was examined by measurements using electro-chemical procedures as well as by numerical

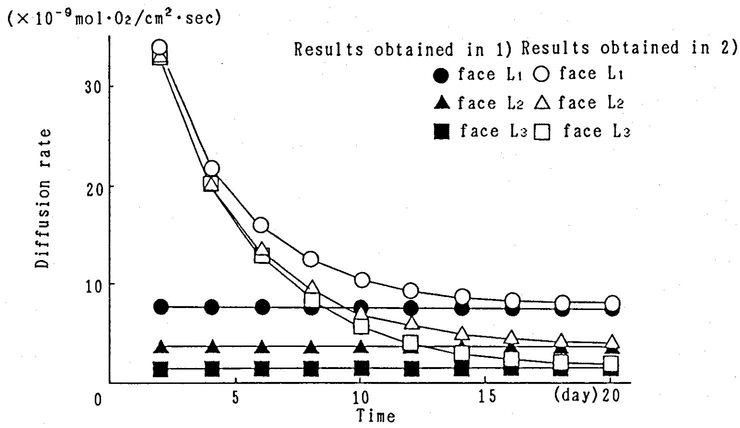


Fig. 16 Relationship between time and diffusion rate

calculations. The main results obtained are summarized below.

(1) No remarkable influence of cover thickness on oxygen transmission was recognized in the range of 3 to 7 cm. Assuming that the diffusion coefficient of oxygen in concrete is not uniform but a layer with a considerably small diffusion coefficient exists in the neighborhood of the reinforcement surface, this fact can be explained well. It can, therefore, be considered appropriate to evaluate the oxygen transmission through concrete by the diffusion rate rather than by the diffusion coefficient.

(2)Oxygen transmission is influenced by initial curing conditions. Concrete cured under water for 3 days has smaller transmissivity than that under sealed condition for 3 days.

(3)Oxygen transmission is also affected by environmental conditions. When ambient temperature is set to be the same, oxygen transmission under water is smaller than that in the air with relative humidity of 85%.

(4)When the height of member is in the range of 40 to 120 cm, no difference was recognized in oxygen transmission due to positions in the height direction.

(5)From numerical calculation using a two-dimensional diffusion model, it was suggested that the oxygen diffusion rate varies with positions on reinforcement surface. On the other hand, within the period of the present test, no significant difference was recognized in the oxygen carry-over rate between two opposite surfaces of reinforcement near and for from concrete surface . This, however, shall be evaluated on basis of further long-term measurement.

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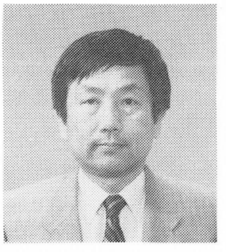
STUDIES ON CONCRETE QUALITY CHANGE AND RELATED FACTORS BASED ON DATA ANALYSES

(Translation from Proceedings of JSCE, Vol. 408, V-11, Aug. 1989)



Toshiyasu TOYOFUKU

SYNOPSIS

The objectives of this study are to analyze factors which are considered to affect concrete quality change and to develope adequate concrete quality control system based on data analyses. The data used in this study are mainly those of the concrete placed in expressway construction works and commonly ready-mixed concrete placed all over Japan.
Through a lot of data analyses, it became evident that concrete qualities become deteriorative and multifarious with range throughout Japan due to producing equipment, quality control system, aggregate condition, regional difference and so on. Comments are also made on those particular factors in order to more reasonable concrete quality control system.

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1. INTRODUCTION

Reacent years, many studies have been reported about the problems of early deterioration or durability decline on concrete structures. As for main reason for this decline, it could be stated that the material to be used and construction methods had become multifarious with the progress of construction works in Japan. Especially, as for the aggregate resources for concrete, though the supply of high quality river aggregate (river sand and gravel) has been decreasing and the kinds of aggregate have been multifarious. Therefore it should be guessed that the concrete qualities (compressive strength, drying shrinkage, freeze-thaw resistance and so on) have also become multifarious. Nevertheless, there are few researches from the viewpoint of studying the relation between the quality of aggregate or the quality control (hereafter QC) and that of concrete at the national scale.

Ready-mixed concrete was merchandised in November 1949, and JIS (Japanese Industrial Standards) A 5308 "Ready-Mixed Concrete" [1] was enacted in November 1953. Moreover, it was the first time that QC of concrete was enacted in the Japan Society of Civil Engineers (JSCE) standard "Standard Specification for Design and Construction of Concrete Structures " (revised edition in 1957) [2]. After that, with the increase of construction works accompanied with the high development of Japan, ready-mixed concrete industry has made remarkable advances. Ready-mixed concrete plants have greatly increased in number all over Japan. The number of factories as of March 1988 is 5354 (the number of JIS plant is 3868, 72.2 % of a whole), and the volume of concrete produced in a year is 17800 milion m^3. Therefore production of the concrete by the field plant is limited only under special conditions.

Nowadays, in the case of the concrete construction works, ready-mixed concrete have been commonly used. QC of concrete is extremely dependent on the manufacturing control of ready-mixed concrete. However, the quality standard of JIS Ready-Mixed Concrete is prescribed at the unloading position. So, manufacturing process which includes the chain from selection of materials, determination of mix proportions, mixing to transportation is being trusted to suppliers by self-imposed restraint controls. Naturally, quality difference of manufactured concrete could be happened depending on the difference of QC systems among the each ready-mixed concrete plants. On the other hand, in the case of NIHON DORO KODAN (Japan Highway Pablic Corporation, hereafter KODAN), the flow of QC system (from start of concrete investigation before order of works, execution control tests under construction works, to finish of inspection after completion of works) should be done consistently. Then the both concrete manufactured by the ready-mixed concrete plants and by the field plants have been controled for the construction by the same specifications [4]~[6]. In these specifications the methods were standardized how to control the concrete qualities and how to inspect these qualities. Judging from these matters, these concretes have been produced and have been maintaining almost constant quality level.

From the above facts, the objectives of this study are to analyze factors which are considered to affect concrete quality changes and to develope adequate concrete QC system based on data analysis. The data used in this study are mainly those of the concrete placed in expressway construction works of KODAN and commonly ready-mixed concrete placed all over Japan [7]~[12].

2. CONTENTS OF THE INVESTIGATION

2.1 Investigation of Concrete Tests

An investigation of Concrete Tests (hereafter Investigation Ⅰ) [12] is the result which was tested on many kinds of concretes (indoor tests, 75 test reports reported by KODAN organizations all over Japan from 1971 to 1985, hereafter CONCRETE TESTS). The contents of investigation are qualities of materials, mix proportions, results of mix design (compressive strength test) and so on. These results have a very wide domain because the data includes low quality aggregate so far not used for actual construction works.

2.2 Investigation of the Concrete placed in Highway Construction Works of KODAN

Investigation of the concrete placed in highway construction works of KODAN (hereafter Investigation Ⅱ) [12] is aimed at the concretes which were placed in highway construction works of KODAN (hereafter KODAN CON).

In this investigation the following concretes were contained [7];
(a) The concrete which was used for construction works of the Meishin Expressway constructed in 1958~1965 when the ready-mixed concrete plants were not so popular (the first expressway in Japan, hereafter MEISHIN)
(b) The concrete which was used for construction works of the Tomei Expressway constructed in 1965~1969 when the aggregate resources started to be multifarious (hereafter TOMEI)
(c) The concrete which is used for construction works of the nationwide highways constructed in 1972~1985 (completion of works in each year, hereafter COMPLETION EACH YEAR).

The data of Investigation Ⅱ did not show the change of concrete quality data at the same construction site because the construction sites have been changed yearly. But because these works are nationwide, these data can be treated equally as random sampling data from all over the country.

The methods of the investigation were based on the way to collect the past data and "the reports of placed concrete" which were drawn up after completion of works [6]. The contents of the investigation were the outline of construction, qualities of materials, mix proportion, result of mix design, specified mix, results of control tests and so on. The number of investigated mix proportions are 19 mixes shown in Table 1. The notations shown in ( ) of this table are the names which are standardized by the KODAN specifications [4]~[6]. For example, in the case of "A_{1-1}", "A" means the type of structures that the concrete placed, the first suffix "$_1$" means the maximam size of coarse aggregate or the type of structures and the second suffix "$_{-1}$" means the type of cement.

2.3 Investigation of the Ready-mixed Concrete

An investigation of the ready-mixed concrete (hereafter Investigation Ⅲ) [12] is aimed at the data on the nationwide ready-mixed concrete plants which were mainly located along the expressways of KODAN under plan, construction or operation. This investigation was conducted in 1978 (hereafter REMI CON '78) and 1986 (hereafter REMI CON '86) [8]~[11].

The method of the investigation was formed by questionnaires. REMI CON '78 was asked the 500 selected plants in June 1978, and got the answer from 432 plants (9.0 % of total number 4808 of ready-mixed concrete plants, 16.4% of total number 2554 of JIS ready-mixed concrete plants) until August 1978. REMI CON '86 was asked selected plants in July 1986, and got the answer from 560 plants (about 10 plants each prefectures, refer to Fig. 1). The investigation were based on the way to select the class of Concrete 1(A_{1-1}), 4(B_{1-1}), 6(B_{2-1}), 9(C_{2-1}), 13(P_{2-2}), 15(T_{1-1}), 16(X_{1-1}) and 18(H_{1-1}) from Fig. 1 in order to contrast the KODAN CON and to represent the whole concrete for civil engineering works. And on these

Table 1 Investigated Concrete (Investigation II)

Item / Class of concete (Concrete)	Type of Concrete structure 1)	Condition of mix proportion: Strength at 28 days f_{ck28} (kgf/cm²) 2)	Slump SL (cm) 2)	Air A (%) 2)	Maximum size of coarse aggregate G_M (mm)	Type of cement 3)	Unit cement content C (kg/m³) 4)	Type of chemical admixture 5)	Mix proportioning strength f_{c28} (kgf/cm²)	'82-'83 Completion of works: Number of data n	Avarege of placed concrete (m³)
1 (A_{1-1})	G	300	8±2.5	4±1	20,25	N	(320),320,350,380	w, aw	356	42	372
2 (B_{0-1})	S	240	8±2.5	4±1	20,25	N	(300),300,300,320	w, aw	284	285	2067
3 (B_{0-2})	S	240	8±2.5	4±1	20,25	H	(300),300,300,320	w, aw	284	11	1177
4 (B_{1-1})	R	240	8±2.5	4±1	20,25	N	(290),280,300,320	w, aw	284	327	6171
5 (B_{1-2})	R	240	8±2.5	4±1	20,25	H	(290),280,300,320	w, aw	284	27	3327
6 (B_{2-1})	K	240	8±2.5	4±1	40	N, B	(280),270,280,300	w, aw	284	242	4153
7 (B_{2-2})	K	240	8±2.5	4±1	40	H	(280),270,280,300	w, aw	284	2	106
8 (C_{1-1})	C	180	8±2.5	4±1	20,25	N, B	(240),230,240,250	w, aw	219	191	1191
9 (C_{2-1})	C	180	8±2.5	4±1	40	N, B	(240),230,240,250	w, aw	219	241	1463
10 (D_{1-1})	D	—	—	—	40	N, B	(215),210,210,220	—	—	31	2270
11 (N_{1-1})	N	180	20±2.5	4±1	20,25	N, B	(–),280	w, aw	180	11	1330
12 (P_{1-2})	P	450	7±1.5	4±1	20,25	H	(450),440,470,500	w, aw	522	0	0
13 (P_{2-2})	P	400	7±1.5	4±1	20,25	H	(400),400,430,460	w, aw	464	97	2428
14 (P_{3-2})	P	350	7±1.5	4±1	20,25	H	(350),350,380,410	w, aw	406	130	962
15 (T_{1-1})	T	180	15±2.5	4±1	40	N, B	(270),270,270,280	w, aw	219	61	16165
16 (X_{1-1})	W	225	15±2.5	4±1	40	N, B	(370),370	w, aw	267	9	579
17 (Y_{1-1})	W	300	15±2.5	4±1	20,25	N, B	(370),370	r, ar	356	128	2567
18 (H_{1-1})	H	Flex. 45	1.5±1	4±1	40	N,H,M,P	(320),300,320,350	w, aw	Flex. 50	25	4357
19 (H_{2-1})	H	Flrx. 45	5±1.5	4±1	40	N,H,M,P	(350),310,330,350	w, aw	Flex. 50	27	1983

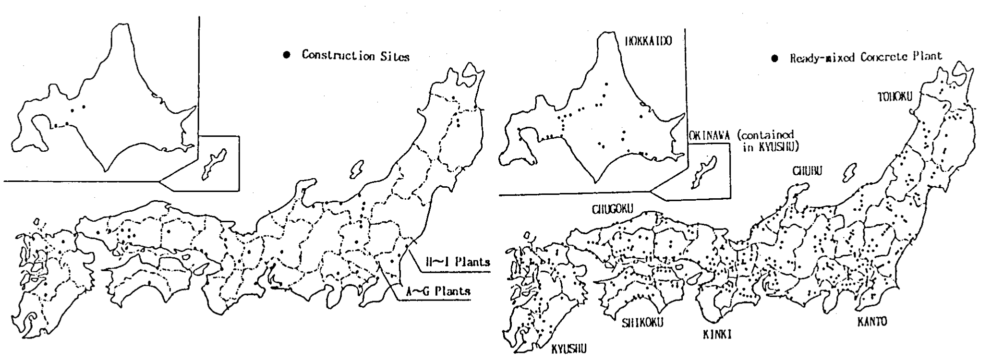
Note 1) G : Deck slab of composite beam bridge, S : Deck slab of general bridge, R : Reinforced concrete structure
K : Foundation of substructure (footing) , C : Plain concrete structure, D : Levelling concrete
N : Fill of pneumatic caisson, P : Prestressed concrete structure, T : Tunnel lining,
W : Foundation of substructure (Underwater concrete), H : Cement concrete pavement slab

Note 2) The value at placing point. The placing point means where concrete is placed within the forms before compacting by vibration.

Note 3) N : Ordinary portland cement, H : High-early-strength portland cement, B : B types of portland blast-furnace slag cement, M : Moderate-heat portland cement, P : Pavement cement

Note 4) (320) : Unit cement content until contracted works in 1977 (example 320 kg/m³)

Note 5) w : Standard types of water-reducing agents, aw : Standard types of air-entraining and water-reducing agents,
r : Retarding types of water-reducing agents, ar : Retarding types of air-entraining and water-reducing agents,
The amount of chemical admixture = (Standard amount of standard types or retarding types of water-reducing agents) + (Amount of air-entraining agents coforming to required air)



(a) Investigation II (compression of works in 1982~1983) (b) Investigation III

Fig. 1 Investigation Points

Standard Goods the quality of materials, mix proportion, result of mix design, specified mix, result of control tests were investigated.

2.4 Investigation of daily control tests

An investigation of daily control tests (hereafter InvestigationⅣ) is aimed at the daily control test data on the concrete placed in JOBAN Expressway construction works of KODAN (13 works, hereafter DALY CONTROL TESTS). Concrete plants are 9 plants located in KANTO district (A～I plants in Fig. 1, the term of September 1980～ April 1985). The contents of investigation were the daily fluctuations of grading of aggregates, surface moisture, batching value, compressive strength and so on.

2.5 Method of analysis

All gathered data were inputted into the Computer ACOS-650 in the Laboratory of KODAN. These data were checked in order to remove the mistakenly filled out data and the calculation mistakes such as W/C ratio, etc.. After this data processing

3. Investigation results and Consideration

3.1 The placed concrete volume of the concrete classes (Investigation Ⅱ and Investigation Ⅲ)

From the result of Investigation Ⅱ, comparisons of the numbers and placed volume of the concrete classes were made. The case of completion of works in 1982 ～1983 (COMPLETION '82～'83, see Fig. 1) are shown in Table. 1 (as an example). On batching plants in the case of completion of works in 1982 the numbers of ready-mixed concrete plants are 143 (97.9 % of a whole, JIS plants are 138 and non JIS plants are 5) and field plants are 3, in the case of completion of works in 1983 the numbers of ready-mixed concrete plants are 123 (98.4 % of a whole, JIS plants are 119 and non JIS plants are 4) and field plants are 2. From this investigation, the placed concrete volume in a year is about 3 millions m^3.

The order of the number of concrete data are concrete 4(B_{1-1}), 2(B_{0-1}), 6(B_{2-1}), 9(C_{2-1}), 8(C_{1-1}), 14(P_{3-1}), 17(Y_{1-1}), 13(P_{2-2}), 15(T_{1-1}) and the order of the number of placed concrete volume are concrete 4(B_{1-1}), 6(B_{2-1}), 15(T_{1-1}), 2(B_{0-1}), 9(C_{2-1}), 17(Y_{1-1}), 13(P_{2-2}), 8(C_{1-1}). Concrete 4(B_{1-1}) which is used for the common RC structures is the most representative concrete. Besides, in the case of investigation Ⅲ, it is also shown the similar tendency. The general quality of these data is compressive strength (age 28 days) f_{c28} = 186～508 kgf/cm², slump SL = 3.0～21.3 cm and air content A = 3.0～4.7 %. The date represent the frequencies of the appearance of the concrete for the road construction works.

Therefore, from now on, an examination will be done about the materials and the concrete of concrete 4(B_{1-1}, in the case of JIS Ready-Mixed Concrete, standard Goods corresponds to this).

3.2 The Materials to be used (Investigation Ⅱ and Investigation Ⅲ)

(1) Cement

Comparing the qualities of cements used in the period of MEISHIN and TOMEI, the specific gravity of cement has been changed from 3.15 to 3.16 since 1972～1975. There is no fluctuation in the fineness value and the compressive strength have been increased by 40 kgf/cm^2 (see Fig.2).

(2) The change of the kinds of aggregate

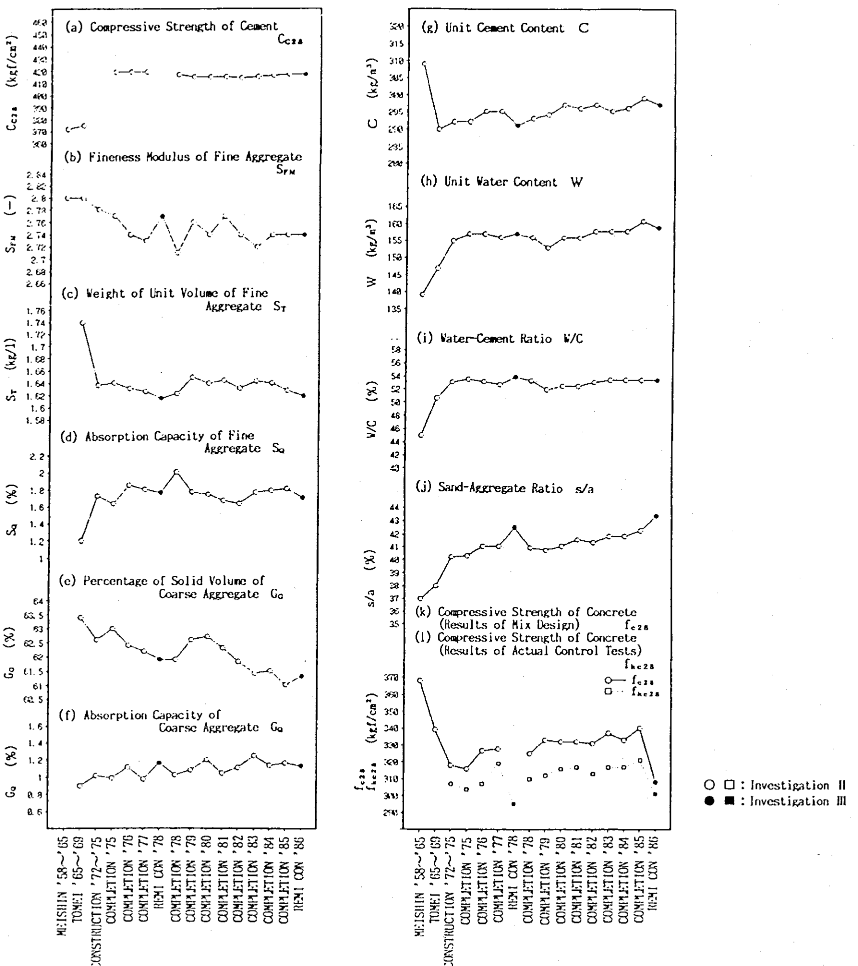


Fig. 2 Changes in qualities of the materials to be used and concretes (Investigation II and Investigation III)

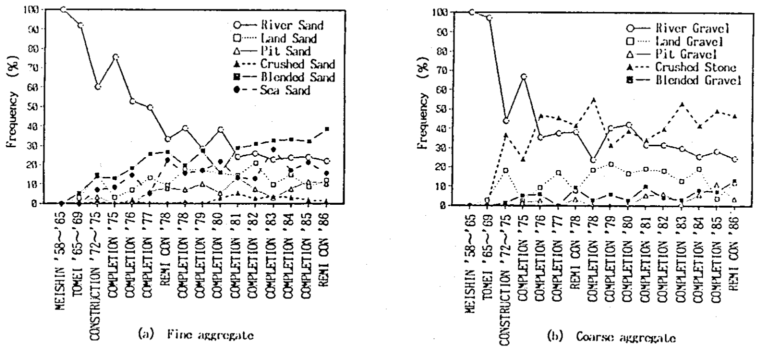


Fig. 3 Changes in kinds of aggregates (Investigation II and Investigation III)

The change of the kinds of aggregate is shown in Fig. 3. In the case of MEISHIN, aggregates used were all river sand and gravel. After about early 1960's, economical development of Japan and expansion of construction enterprise caused the exhaustion of the high quality river aggregates. Since 1966 the Ministry of Construction started actively to give administrative guidance on the regulations of using river gravels and the conversion to use crushed stones. But in the case of TOMEI, only land aggregate, blended sand with pit sand et al. were used because it was blessed with the resources of river sand and gravel. In the early 1970's, the construction of highway had been expanded all over Japan. The aggregate qualities became multifarious under the social conditions on aggregate for concrete. In the case of fine aggregate, the rate of land sand, pit sand, sea sand or these blended sand to be used became high. In the late 1970's,in accordance with the decrease in rate of river sand, that of blended sand increased. Since then this trend has been progressing. On the other hand, in the case of coarse aggregate, accompanying with the decrease in rate of river gravel,that of crushed stone increased. Also land gravel and pit gravel had been used. In the late 1970's, the rate of river gravel and that of crushed stone were reversed. From the early 1980's, it seemed that the rate of river gravel and land gravel tend to decrease and that of crushed stone tends to increase. In Fig. 3, these trends are shown evidently. Seeing the case of REMI CON '86, in the case of fine aggregate, in contrast to the ratio of river sand dropped to 21.8 %, that of blended sand and sea sand rose to 38.9 % and 15.4 % respectively. In the case of coarse aggregate, the rate of river gravel and crushed stone are 24.5 % and 46.7 % respectively. That of crushed stone increased (see later Table 4).

Comparing the fine aggregate with the coarse aggregate, with the decrease in resources of river sand and gravel, in the case of the coarse aggregate, mainly crushed stone and land gravel have replaced river gravel. On the other hand, in the case of the fine aggregate, first blended sand, and the individual sands (such as pit sand, land sand, sea sand) have replaced river sand. As for the reason why the rate of blended sand became high, the followings are given:
If individual sands are used, qualities of these sands (grading, particle shapes, chloride content et al., instead of river sand) have often caused problems. The adjustment of grading is more difficult than that of coarse aggregate, and crushed sand which is by-product of crushed stone should be utilized effectively et al..

Like this, with decrease of river sand and gravel, the aggegate resources have became multifarious, especially in the case of fine aggregate this multifarious trend is remarkable, and the rate of blended sand is most high.

(3) Change of Qualities of Aggregate

With the stated changes on aggregate resources, the qualities of aggregate have changed as shown in Fig. 2. Comparing with the time when river sand and gravel were mainly used in MEISHIN and TOMEI, the aggregates to be used have become multifarious since 1972. In the case of fine aggregate, fineness modulus, solid volume percentage, mass of unit volume and specific gravity become small, and absorption capacity become large. And, in the case of coarse aggregate, mass of unit volume, fineness modulus and solid volume percentage become small, and absorption capacity and specific gravity become large and big. Without specific gravity of coarse aggregate, all qualities become deteorated. In other words, these qualities have changed into the bad side that drying shrinkage (unit water content) of concrete increase or compressive strength, Young's modulus and freeze-thaw resistance decrease [13].

Then, after the early 1970's, as long as the average values are compared each other, the qualities have a little tendency toword deterioration, but almost remain on the same level. As mentioned above, followings could be summarized: The fine aggregates which have good quality and can be used individually have decreased. The fine aggregates are supplemented their deteriorations of qualities by using blended sands. And, the coarse aggregates are supplemented their deterioration of quality by using crushed stone which have the angular shapes (particle shapes are inferior), but have almost good qualities of aggregate. However, as the aggregate to be used have became multifarious, the distribution range of aggregate have became wide.

(4) Qualities of each kind of aggregates

The qualities of each kind of aggregates, in the case of REMI CON '86, are shown in Tables 2 and 3, respectively.

In the case of fine aggregate, river sand which is seemed to have good quality tents to have good trend generally, but absorption capacity is large, together with land sand, and the decline of qualities of aggregate is recognized. Comparing with river sand, land sand and pit sand, the specific gravity, mass of unit volume and solid volume percentage of sea sand are low (quality is bad) and absorption capacity, finess modulus and loss in washing test are also low (quality is good). In the case of crushed sand, specific gravity and mass of unit volume are large, and absorption capacity is low (qualities of aggregate are good), but finess modulus and loss in washing test are large (unit water content increase). In the case of blended sand the next features is recognized that a

Table 2 Quality of Fine Aggregate (Investigation Ⅲ)

Kinds of aggregate (Item →)		Fineness modulus S_{FM} (−)				Loss in washing test S_A (%)				Percentage of solid volume S_O (%)				Weight of unit volume S_T (kgf/l)				Specific gravity S_H (−)				Absorption capacity S_Q (%)			
		$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}
	River Sand	2.78	0.11	2.99	2.34	1.5	0.6	2.8	0.1	64.3	2.0	71.6	57.8	1.637	0.061	1.840	1.450	2.59	0.03	2.71	2.52	1.79	0.58	3.58	0.65
	Land Sand	2.73	0.11	3.00	2.45	1.3	0.6	2.8	0.2	65.1	2.3	70.2	60.8	1.658	0.075	1.860	1.520	2.59	0.04	2.75	2.52	1.82	0.65	3.26	0.50
	Pit Sand	2.74	0.15	2.91	2.04	1.7	0.5	2.6	0.6	64.7	1.8	69.4	60.7	1.638	0.054	1.780	1.540	2.57	0.02	2.62	2.52	1.66	0.39	2.73	1.04
	Sea Sand	2.70	0.09	2.88	2.50	1.1	0.5	2.5	0.3	61.9	2.1	67.9	57.0	1.588	0.068	1.800	1.420	2.56	0.03	2.68	2.52	1.65	0.37	2.80	1.11
	Crushed Sand	2.80	0.07	2.92	2.74	1.8	1.7	4.8	0.2	64.6	4.3	72.5	58.6	1.685	0.127	1.920	1.570	2.64	0.06	2.73	2.56	1.33	0.65	2.30	0.46
Blended Sands	River+Land	2.72	0.10	2.95	2.50	1.5	0.5	2.9	0.3	63.8	1.8	67.3	60.0	1.616	0.053	1.730	1.505	2.58	0.02	2.65	2.54	1.74	0.44	2.93	1.02
Blended Sands	River+Pit	2.80	0.10	2.97	2.53	1.4	0.6	2.4	0.2	63.5	2.1	66.2	58.2	1.604	0.054	1.680	1.430	2.57	0.03	2.62	2.52	1.69	0.60	2.38	0.13
Blended Sands	River+Sea	2.77	0.11	3.05	2.57	1.4	0.4	2.0	0.4	63.8	1.8	67.2	61.1	1.634	0.053	1.745	1.520	2.60	0.03	2.64	2.54	1.59	0.39	2.35	1.04
Blended Sands	River+Crushed	2.78	0.07	2.89	2.62	2.3	0.9	4.7	1.1	64.8	2.5	68.9	61.5	1.665	0.066	1.760	1.550	2.61	0.03	2.65	2.57	1.75	0.49	2.75	0.83
Blended Sands	Land +Pit	2.71	0.11	2.94	2.45	1.6	0.5	2.6	0.7	64.5	2.1	68.7	61.6	1.625	0.060	1.745	1.530	2.57	0.02	2.61	2.54	1.96	0.57	3.12	1.29
Blended Sands	Land +Sea	2.79	0.10	2.89	2.60	1.5	0.5	2.1	0.9	64.4	1.4	66.4	62.9	1.632	0.044	1.690	1.573	2.58	0.04	2.64	2.54	1.90	0.52	2.79	1.29
Blended Sands	Land +Crush	2.71	0.11	2.89	2.42	1.9	0.9	3.7	0.8	63.5	1.5	65.9	60.8	1.629	0.054	1.710	1.557	2.61	0.04	2.68	2.55	1.64	0.40	2.34	0.83
Blended Sands	Pit +Sea	2.76	0.11	2.90	2.57	1.7	0.4	2.1	1.0	63.2	2.5	69.0	59.6	1.586	0.071	1.730	1.470	2.55	0.02	2.60	2.50	1.85	0.37	2.60	1.30
Blended Sands	Pit +Crushed	2.67	0.18	2.99	2.30	1.9	0.8	3.8	0.4	63.3	1.9	67.9	59.9	1.625	0.056	1.759	1.530	2.61	0.03	2.65	2.57	1.57	0.34	2.14	1.10
Blended Sands	Sea +Crushed	2.72	0.10	2.90	2.34	1.9	0.9	4.5	0.4	62.8	1.6	65.9	58.6	1.598	0.057	1.768	1.480	2.59	0.06	2.82	2.54	1.57	0.39	2.25	0.73
Blended Sands	Total	2.73	0.11	3.05	2.30	1.7	0.7	4.7	0.2	63.6	2.0	69.0	56.2	1.617	0.058	1.768	1.430	2.59	0.04	2.82	2.50	1.71	0.46	3.12	0.13
Total		2.74	0.11	3.05	2.04	1.5	0.7	4.8	0.1	63.8	2.3	72.5	56.2	1.621	0.070	1.920	1.420	2.56	0.04	2.82	2.50	1.72	0.50	3.58	0.13

Notes : Number of data is Table 4. $\bar{x}$: Average value, x_σ : Standard deviation, x_{max} : Maximum value, x_{min} : Minimum value

Table 3 Quality of Coarse Aggregate (Maximam size 25mm, Investigation Ⅲ)

Kinds of aggregate (Item →)		Percentage of solid volume G_O (%)				Weight of unit volume G_T (kgf/l)				Specific gravity G_H (−)				Absorption capacity G_Q (%)				Content of soft particle G_Y (%)				Soundness G_D (%)			
		$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}	$\bar{x}$	x_σ	x_{max}	x_{min}
	River gravel	63.5	1.4	67.7	60.4	1.655	0.048	1.827	1.549	2.64	0.04	2.80	2.49	1.24	0.54	3.56	0.48	1.9	1.3	7.4	0	4.8	0.3	14.8	0.3
	Land gravel	64.0	1.5	68.2	60.0	1.652	0.049	1.810	1.540	2.62	0.04	2.73	2.52	1.49	0.72	3.63	0.30	2.7	2.6	19.3	0	4.6	2.4	11.2	0
	Pit gravel	63.9	1.8	66.6	60.3	1.647	0.047	1.715	1.550	2.60	0.01	2.65	2.59	1.11	0.39	1.73	0.45	2.4	1.4	4.5	0.1	4.4	1.8	9.0	1.0
	Crushed stone	59.1	1.3	63.4	56.1	1.580	0.060	1.770	1.460	2.70	0.09	3.05	2.52	1.00	0.55	2.74	0.25	1.2	1.3	8.1	0	3.7	2.0	12.6	0
Blended gravels	River+Land	62.8	1.2	64.1	61.4	1.636	0.039	1.678	1.570	2.64	0.03	2.68	2.60	1.33	0.33	1.66	0.90	2.0	1.2	4.3	1.1	4.5	1.7	6.7	1.5
Blended gravels	River+Pit	63.9	1.2	65.5	62.7	1.665	0.021	1.690	1.640	2.64	0.03	2.68	2.61	1.45	0.65	2.42	1.10	2.7	1.2	4.4	1.9	5.3	3.6	10.3	1.8
Blended gravels	River+Crushed	62.0	1.3	64.6	58.5	1.627	0.037	1.678	1.545	2.65	0.03	2.70	2.60	0.98	0.27	1.56	0.42	1.6	1.2	3.9	0	4.0	1.9	6.7	0.3
Blended gravels	Land +Crushed	62.1	1.4	64.4	60.1	1.625	0.041	1.705	1.560	2.65	0.02	2.68	2.60	1.05	0.38	1.77	0.64	2.1	1.2	3.8	0	4.6	2.3	8.4	1.4
Blended gravels	Pit +Crushed	60.7	1.3	62.3	58.1	1.586	0.036	1.620	1.510	2.64	0.01	2.66	2.62	0.83	0.20	1.18	0.50	1.5	1.2	3.3	0	3.4	1.7	6.9	1.7
Blended gravels	Sea +Crushed	60.4	2.4	62.1	58.7	1.615	0.036	1.640	1.589	2.69	0.04	2.72	2.66	0.56	0.21	0.70	0.41	0.8	0.4	1.0	0.5	3.0	0.8	3.5	2.4
Blended gravels	Total	62.0	1.5	65.5	58.1	1.624	0.040	1.705	1.510	2.65	0.03	2.72	2.60	1.04	0.38	2.42	0.41	1.8	1.3	4.7	0	4.2	2.1	10.3	0.3
Total		61.3	2.5	68.2	56.1	1.616	0.063	1.827	1.460	2.67	0.08	3.05	2.49	1.13	0.57	3.63	0.25	1.7	1.6	19.3	0	4.2	2.3	14.8	0

Note : Number of data is Table 4.

blend of sea sand (in order to adjust mainly the chloride content) caused consequently the increase of mass of unit volume (improvement of quality is caused), and a blend of crushed sand caused the increase of specific gravity and loss in washing test et al.. Comparing the quality of river sand with that of TOMEI (almost river sand was used, see Fig. 2), it is noticed that all the items of quality areon the bad side and even in the case of river sand the qualities turn deteriorative.

In the case of coarse aggregate, when the quality of crushed stone is compared with river gravel, land gravel and pit gravel, mass of unit volume and solid volume percentage are low and shape of particles is bad, but specific gravity, absorption capacity, soundness and soft particles are low, and quality of aggregate becomes good. As compared with the individual of crushed stone, the blended gravel which is blended with crushed stone have a large mass of unit volume and a large solid volume percentage, and qualities become improved. Comparing the quality of river gravel with that of TOMEI (almost river gravel was used, see Fig. 2), specific gravity is low and absorption capacity is large, and qualities are on the bad side. As river sand, even in the case of river gravel the qualities turn deteriorative.

3.3 Concrete (Investigation II and Investigation III)

(1) Change of qualities of concrete

Comparing also with the case of concrete 4(B_{1-1}), the change of qualities of concrete is shown in Fig. 2. With the change of the aggreates to be used, the unit water content increases by 20 kg/m^3 more than that of MEISHIN, and also increases by 10kg/m^3 more than that of TOMEI. And the sand-aggregate ratio increases by 4 % more than that of MEISHIN, and also increases by 2 % more than that of TOMEI. After the early 1970's, the former increases by 1~2 kg/m^3 and the latter increases by 1~2 %, and the trend of slight increase is recognized. As discussed above, this reason was that:
As the river sand and gravel which have good shape of perticles have decreased, the crushed stone and sea sand which have angular and flat shape of perticles have increased and the fine and coarse aggregates became multifarious. And in order to get the same workability of concrete, it is needed that unit water

Table 4 Combinations of Fine Aggregate and Coarse Aggregate (Investigation III)

Coarse Aggregates \ Fine Aggregates		River Sand	Land Sand	Pit Sand	Sea Sand	Crushed Sand	Blended Sands: River+ Land	River+ Pit	River+ Sea	River+ Crushed	Land + Pit	Land + Sea	Land + Crushed	Pit + Sea	Pit + Crushed	Sea + Crushed	Sub-total	Total
River Gravel		93 (16.9)	9 (1.6)	2 (0.4)	1 (0.2)	1 (0.2)	9 (1.6)	7 (1.3)	8 (1.5)	4 (0.7)	0	0	0	1 (0.2)	0	0	29 (5.3)	135 (24.5)
Land Gravel		4 (0.7)	38 (6.9)	2 (0.4)	0	0	9 (1.6)	1 (0.2)	0	1 (0.2)	5 (0.9)	3 (0.5)	1 (0.2)	1 (0.2)	0	0	21 (3.8)	65 (11.8)
Pit Gravel		0	0	20 (3.6)	0	0	0	0	0	0	0	0	0	0	0	0	0	20 (3.6)
Crushed Stone		17 (3.1)	14 (2.5)	22 (4.0)	82 (14.9)	6 (1.1)	8 (1.5)	5 (0.9)	5 (0.9)	5 (0.9)	16 (2.9)	3 (0.5)	13 (2.4)	11 (2.0)	14 (2.5)	36 (6.5)	116 (21.1)	257 (46.7)
Blended Gravels	River+ Land	0	0	0	1 (0.2)	0	5 (0.9)	0	0	0	0	0	0	0	0	0	5 (0.9)	6 (1.1)
	River+ Pit	0	0	0	0	0	0	4 (0.7)	0	0	0	0	0	0	0	0	4 (0.7)	4 (0.7)
	River+ Sea	0	0	0	0	0	0	1 (0.2)	0	0	0	0	0	0	0	0	1 (0.2)	1 (0.2)
	River+Crushed	5 (0.9)	3 (0.5)	5 (0.9)	1 (0.2)	0	11 (2.0)	2 (0.4)	5 (0.9)	4 (0.7)	0	0	0	1 (0.2)	1 (0.2)	1 (0.2)	25 (4.5)	39 (7.1)
	Land +Crushed	1 (0.2)	3 (0.5)	2 (0.4)	0	0	2 (0.4)	0	0	0	1 (0.2)	0	4 (0.7)	0	0	0	7 (1.3)	13 (2.4)
	Pit +Crushed	0	0	4 (0.7)	0	0	0	3 (0.5)	0	0	0	0	0	0	1 (0.2)	0	4 (0.7)	8 (1.5)
	Sea +Crushed	0	0	0	0	0	0	0	1 (0.2)	0	0	0	0	0	0	1 (0.2)	2 (0.4)	2 (0.4)
	Subtotal	6 (1.1)	6 (1.1)	11 (2.0)	2 (0.4)	0	18 (3.3)	10 (1.8)	6 (1.1)	4 (0.7)	1 (0.2)	0	4 (0.7)	1 (0.2)	2 (0.4)	2 (0.4)	48 (8.7)	73 (13.3)
Total		120 (21.8)	67 (12.2)	57 (10.4)	85 (15.4)	7 (1.3)	44 (8.0)	23 (4.2)	19 (3.5)	14 (2.5)	22 (4.0)	6 (1.1)	18 (3.3)	14 (2.5)	16 (2.9)	38 (6.9)	214 (38.9)	550 (100)

Note : Upper side : Number of Concrete Plants, Lower side : Constitution Ratio (%)

content increases and sand-aggregate ratio also increases.

Though compressive strength changes as mix proportioning strength changes, it remains on the almost same level. With this trend, there are almost no fluctuations also in the water-cement ratio. The unit water content and the unit cement content are slitely increased.

(2) Qualities (kinds) of Aggregate and Qualities of Concrete

Table 4 shows the combinations of fine aggregate and coarse aggregate to be used (the examples from REMI CON '86). There are great differences among ready-mixed concrete plants concerning their aggregate conditions. The order of numbers of combination is that:
river sand and river gravel = 16.9 %, sea sand and crushed stone = 14.9 %, land sand and land gravel = 6.9 %, blended sand (sea sand and crushed sand) and crushed stone = 6.5 %, pit sand and crushed stone = 4.0 %, pit sand and pit gravel = 3.6 %, river sand and crushed stone = 3.1 %, blended sand (land sand and pit sand) and crushed stone = 2.9 %, etc..
The maximum number of combination is blended sands and crushed stone (21.1 %).

As a whole, there are a large number of combinations that the production areas

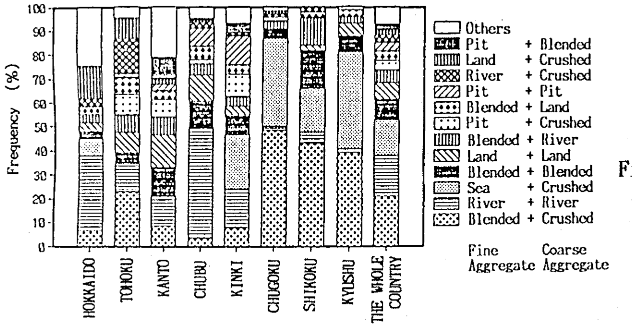


Fig.4 Combinations of fine aggregate and coarse aggregate at diffrent districts (Investigation Ⅲ)

Table 5 The kinds of Aggregate and Concrete Qualities (Ready-mixed Concrete corresponds to Concrete $4(B_{1-1})$, Investigation Ⅲ)

Case	Coarse Aggregate	Fine Aggregate (Items)	Number of data n	Maximum Size of Coarse Aggregate G_M (mm) $\bar{X}$	X_σ	X_{max}	X_{min}	Unit Cement Content C (kg/m³) $\bar{X}$	X_σ	X_{max}	X_{min}	Unit Water Content W (kg/m³) $\bar{X}$	X_σ	X_{max}	X_{min}	Water-Cement Ratio W/C (%) $\bar{X}$	X_σ	X_{max}	X_{min}	Sand-Aggregate Ratio s/a (%) $\bar{X}$	X_σ	X_{max}	X_{min}	Compressive Strength at mix design f_{c28} (kgf/cm²) $\bar{X}$	X_σ	X_{max}	X_{min}
1	Gravel	Normal		25								145				55				38							
2	River	River	93	25	0	25	25	288	13	318	259	152	6	164	136	52.8	2.1	56.8	47.9	42.1	2.0	47.3	36.9	305	15	362	278
		Blended	29	25	1	25	20	291	14	316	266	153	7	169	141	52.4	1.9	56.0	49.0	41.7	2.0	45.4	36.6	299	14	331	273
	Land	Land	38	25	0	25	25	287	15	315	255	150	5	160	140	52.3	2.3	56.0	47.0	41.8	1.9	45.4	37.4	304	18	360	260
		Blended	21	25	2	25	20	293	13	317	272	153	8	162	143	52.4	2.1	57.0	49.0	42.5	2.0	46.9	37.5	303	11	323	283
	Pit	Pit	20	25	0	25	25	292	12	317	274	152	4	159	146	52.1	1.8	54.9	47.3	41.3	1.8	45.2	38.1	316	17	353	289
	Crushed	River	17	24	2	25	20	306	12	326	275	163	6	176	149	53.3	1.0	55.0	50.8	43.4	2.2	46.7	37.3	314	21	355	276
		Land	14	24	2	25	20	295	17	324	263	159	7	169	143	53.9	2.3	58.4	50.0	44.0	2.0	46.1	40.1	308	14	343	291
		Pit	22	22	3	25	20	292	23	325	243	161	6	169	148	55.3	2.9	62.1	50.0	44.4	1.6	47.6	40.6	313	16	349	284
		Sea	82	20	1	25	20	315	12	340	272	169	5	182	147	53.8	1.5	58.4	50.0	44.6	1.1	46.9	41.0	305	15	337	263
		Blended	116	21	2	25	20	306	15	343	255	166	7	182	143	54.2	1.9	60.0	49.0	44.8	1.6	49.5	38.5	310	17	362	280
	Blended	Pit	11	25	0	25	25	278	16	300	256	153	6	163	146	55.3	1.8	57.4	52.9	42.8	1.5	45.7	41.1	310	19	352	292
		Blended	48	24	2	25	20	290	14	322	262	157	7	170	141	54.0	1.7	58.4	49.8	42.8	2.4	48.1	36.9	309	13	333	285
	Total	Total	550	23	2	25	20	297	18	343	243	159	10	182	136	53.5	2.2	62.4	47.0	43.3	2.3	49.5	35.5	308	16	362	260

Case 1) : The value from Table C 4.8.1 in Standard Specification for Design and Construction of Concrete Structures, Part 2 (Construction). Sand (fineness modulus = about 2.80) of ordinary gradations as aggregates.
Case 2) : The value from Investigation Ⅲ. In the case of maximum size of coarse aggregate=20・25mm, Slump=8cm and n>10.

for fine aggregate is the same as that for coarse aggregate. However, as for crushed stone, there are various combinations because it is used widely throughout Japan. So, it ranks 1/2 of a whole (see Fig. 4).

Therefore, in order to consider the infuluence of fine and coarse aggregate to concrete quality, the relationships between the each kinds of coarse aggregate and mix proportions or compressive strength are shown in Table 5. The concrete made up of crushed stone needs more unit cement content, unit water content and water-cement ratio than that made up of river gravel, land gravel and pit gravel. The reason for this is as follows:
Because the particle shapes of crushed stone is angular and flowability is inferior, unit water content to get the required slump is needed much more value. But because the cohesion between the surface of aggregate and cement paste is good, and comparing with river gravel, it has good qualities of aggregate such as specific gravity, absorption capacity and so on. Even if the water-cement ratio is large, required strength can be fulfiled [13], [14].

Furthermore, as for the concrete made up of crushed stone, comparing the relationship between the kinds of fine aggregates and mix proportions (or compressive strength), it is shown that the different kinds of fine aggregates influence to mix proportion and compressive strength greatly. The average value of unit water content of sea sand is higher by 10 kg/m^3 than that of land sand, unit cement content is also higher by 20 kg/m^3 than that and water-cement ratio is lower by 0.3 % than that. But compressive strength is lower by 3 kgf/cm^2 than that. In the case of blended sand, there is no constant trend. But, in the case of sea sand, blending tends to cause high strength although it has low unit cement content. It is understood that blending may causea improvement of quality.

Consequently a regional difference of concrete has arisen (see Fig.5) [9], [11]. In the region where the sea sand and crushed stone are used, unit water content and unit cement content are high, but on the other hand strength index is low and compressive strength is low as well. Where, strength index is defined by (b/W)

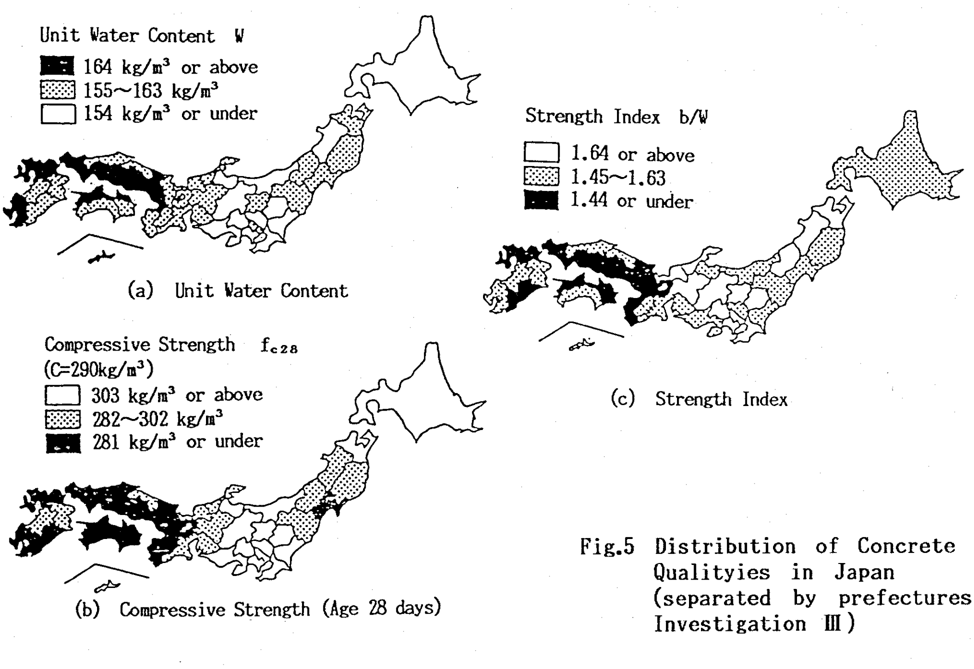


Fig.5 Distribution of Concrete Qualityies in Japan (separated by prefectures, Investigation III)

which is adopted from an equation [11], [12]:

$$f_{c28} = a + b \cdot (C/W)$$

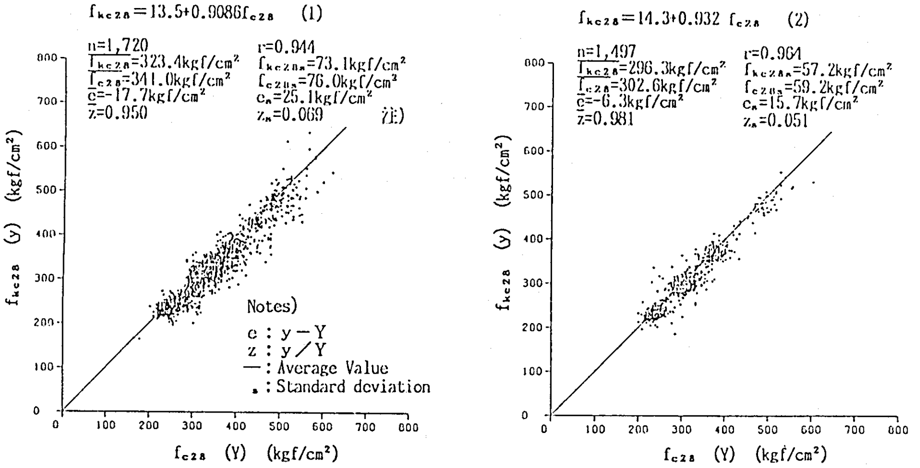
When approximate values of sand-aggregate ratio and unit water content (which have been given in Table C4.8.1 of "Standard Specification for Design and Construction of Concrete Structures" [2]) are compared with the present, it is shownthat unit water content is low by 7 kg/m³ and sand-aggregate ratio is low by 4%.Considering the kinds of combination of aggregate are numerous, the author proposes revising the approximate values and correction values. The values in Table 5 are proposed as standard ones, and also the values in Table 10 of the reference [12] are proposed as correction ones.

3.4 QC and Quality of Concrete (Investigation I ~ Investigation IV)

(1) Relation between compressive strength of the actual control test results (actual results of shipment) and compressive strength of the mix design results (trial mixtures results)

From Fig. 2 (k) and (l), searching for the relation between average value f_{KC28} of compressive strength of the actual control test results (actual results of shipment of REMI CON) f_{KC28}' and the compressive strength of the mix design results (trial mixtures results, tested in the test room) f_{C28}, in the case of KODAN CON, the former is lower by 3~7 % (average value) than the latter. When this relation is searched in representive COMPLETION '82~'83 (see Fig. 6(a) and equation (1)), there is the high correlation between f_{kc28} and f_{c28} (correlation coefficient r = 0.944, standard error e_s = 25.1 kgf/cm²). The value $z = f_{kc28}/f_{c28}$ is in the range of 1.20 ~0.67, and the strength is low by 5.0 % (average value, 17.7 kgf/cm²).

On the other hand, in the case of REMI CON, when this relation is also searched in representive REMI CON '86 (see Fig. 6(b) and equation (2)), there is the high correlation (r = 0.964, e_s = 15.7 kgf/cm²). The average value of strength is low by 6.3 kgf/cm² (1.9 %), and that value is smaller by 11 kgf/cm² than KODAN CON. However, from Fig. 2, in spite of almost same qualities of the materials to be used and almost same water-cement ratio, both f_{kc28} and f_{c28} are lower than KODAN



(a) KODAN CON (Investigation II) (b) REMI CON (Investigation II)

Fig. 6 Relation between f_{kc28} and f_{c28}

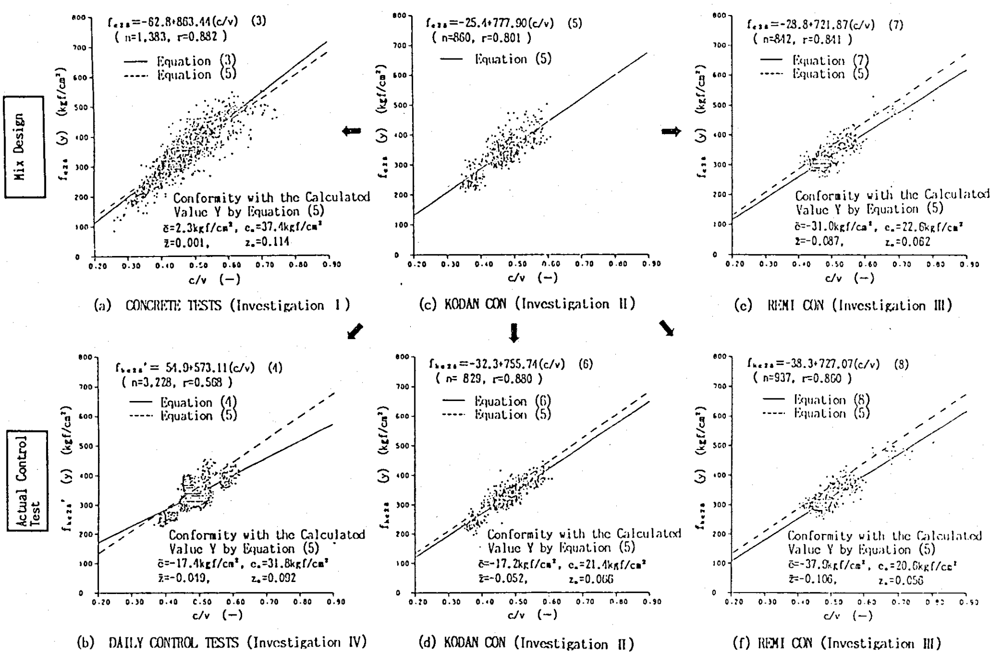


Fig. 7 Relation between compressive strength and cement-void ratio

Con and the tendency is different. The reason for this will be considered in the following section.

(2) Influence of QC against Quality of Concrete

From the results of Investigation I ~ IV, Fig. 7 shows the relations between compressive strength f_{kc28} (or f_{c28}) and cement-void ratio c/v in the case of the concrete in which ordinary portland cement, maximum size of coarse aggregate = 20 or 25 mm and air-entraining and water-reducing agents are used. All of them are closely correlated. In the case of the mix design results, KODAN CON is almost equal to the indoor test results of CONCRETE TESTS (Investigation I), but the compressive strength of KODAN CON is higher by 31 kgf/cm^2 (8.7%) in average than that of REMI CON (Investigation III). In the case of the actual control test results, the compressive strength of KODAN CON is lower by about 5 % (DAILY CONTROL TESTS = 4.9%, KODAN CON = 5.2%) than that of the mix design results but REMI CON is lower by 10.6% (average value 38 kgf/cm^2) than that, and the amount of drop is considerable.

As for the reason for this, it is judged that concrete quality at shipment is determined by the differences of quality variations (drop) of manufacturing facilities and quality control conditions against the strength of mix design that is essentially what is true concrete quality. Giving concrete examples, there are differences of mixing efficiency of mixers [15], differences of curing conditions, differences of grading of aggregate, errors in correction of over and under particle-size, mixture of farmful amount of mud and dust in aggregates, errors in correction of surface moisture, use of sludge water or not, variation of concrete temperature (weather conditions), transport method, variation of transport time, residual substance of sludge water, etc., slump and air content

Table 6 Ready-mixed Concrete Plants (Nomber of Investigated Plants= 243)

No	Mainly pointed out matters or advised matters	Number of matters (frequency) amount (%)
1	Badness of maintenance and cleaning in various places of plant	167 (68.7)
2	The remainder aggregates at belt conveyor, turnhead and batching hopper	115 (47.3)
3	Unpreparedness of shed of stock yard	78 (32.1)
4	Inadequate drainage at stock yard and plant yard	71 (29.2)
5	Insufficient height of partition wall of colgate silo and stock yard	58 (23.9)
6	Lack of test implements and equipments	53 (21.8)
7	Lack of testers	49 (20.2)
8	Unpreparedness or unsuitable position of belt comveyor cleaner	44 (18.1)
9	Unpreparedness of cover of belt conveyor	42 (17.3)
10	Leakage of mixing water and chemical admixtures from batching hopper, etc.	39 (16.0)
11	Lack of volume and number of stock yard, colgate silo	34 (14.0)
12	Unreasonable indication of kinds of aggregate and cements	30 (12.3)
13	Unreasonable grading and particle shape of aggregate, insufficiency of washing	29 (11.9)
14	Number shortage on correction of surface moisture of aggregate	23 (9.5)
15	Remaining concrete inside mixer, leakage from gate	21 (8.6)
16	Unpreparedness or unsuitable position of monitor television	17 (7.0)
17	Certain action of monthly quality control and daily control tests	17 (7.0)
18	Badness of batching equipments	17 (7.0)
19	Unpreparedness of prevention equipment for overweighing chemical admixtures	14 (5.8)
20	Uses of sludge water	12 (4.9)

also drop. Therefore at the stage of mix design it is supposed that there are many cases that the specified mix of REMI CON was determined from actual results of shipment without actual mix design (trial mixtures tested in test room). The ratio is 27% of a whole according to questionnaires (REMI CON '78).

Table 6 shows the main matters which are advised the inspected supplier's plants on improvement of manufacturing facilities and the method of quality control at inspection of plants in 1983~1985 [3]. The matters pointed out are influencing items on quality variation of aggregate, influencing items on quality variation because of bad facilities, influencing items on quality variation because of bad control, etc.. Like this, manufacturing techniques of JIS Ready-Mixed Concrete have made great advandes during last 40 years, but under the present situation there are many cases that quality control system includes some problems for steady manufacturing. Then, from Fig. 2 (j), in the case of the mix proportion of REMI CON, sand-aggregate ratio is larger than that of KODAN which decided the most suitable sand-aggregate ratio by test mix, in spite of almost same water-cement ratio. This tendency is recognized generally, and this fact became a factor increasing the unit water conent. Moreover, Fig. 8 shows the concrete volumes (average value of each plants) which are calculated from the specific gravity of materials, speciffied mix and air content of actual results of shipment. Because the method to calculate the mix peoportions does not standardized in JIS, the range of concrete volume is 0.992~1.025 m^3 and it is generally over 1 m^3, and this volume error (mix proportion error) bring about more error to batching error.

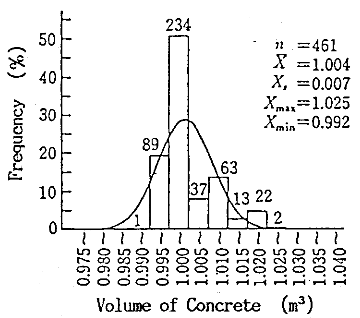


Fig. 8 Concrete Volume (Investigation Ⅲ)

Judging from above mentioned facts, the qualities of ready-mixed concretes are varied according to the system of inspection and advice by purchaser (supervisor), manufacturing facilities of plants, the system of quality control, the calculating method of mix proportion, the situation of aggregate, weather condition, regional character et al.. Therefore it is considered that the great differences among plants have arisen due to these factors.

4. CONCLUSIONS

As the results of this study the followings are obtained:

(1) As for the aggregate resources for concrete in Japan, the high quality river sand and gravel have been decreasing, and the kinds of aggregates have become deteriorative and multifarious. This trend is especially remarkable on fine aggregates.

(2) Nowadays, in Japan, the representative aggregates which are used in the concrete are blended sand as fine aggregate and crushed stone as coarse aggregate. The ratio of concrete which use this combination of aggregates is the most highest one. The crushed stone concrete accounts for about 1/2 of a whole.

(3) The qualities of ready-mixed concretes are greatly influenced by aggregates to be used. The regional differences of concretes have arisen.

(4) It is generally recognized that the compressive strength of concrete at shipment (actual concrete test results) is lower than that of concrete at mix design (trial mixtures), the tendency that arise strength drop is recognized as a whole. It is considered that the amount of drop depends on system of quality control. In the case of excellent quality control the average amount of drop is about 5% and in the case of common quality control it is about 10%.

(5) According to the system of inspection and advice by purchaser (supervisor), manufactuting facilities of plants, the system of quality control, the calculating method of mix proportion, the sutuation of aggregate, weather condition, regional charactor et al., the qualities of ready-mixed concretes are varied among plants.

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