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QUANTITATIVE EVALUATION OF NON-UNIFORM QUALITY OF CONCRETE IN RC MEMBERS

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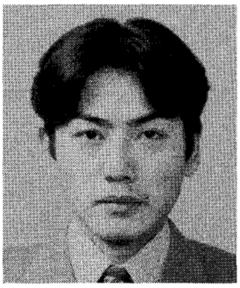

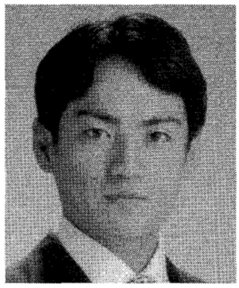
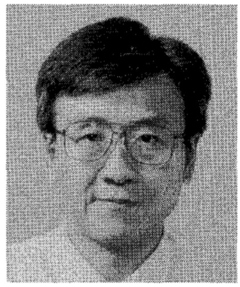

Tetsuya ISHIDA Tomoharu KATO Sou NINOMIYA Koichi MAEKAWA

The objective of this study is to evaluate non-uniform quality of concrete materials as actually obtained in RC structures. In order to quantify the influences of structural size, reinforcement arrangement, slump value, and construction methods on segregation, RC column and beam specimens are fabricated. As a material parameter representing segregation, the porosity of core specimens taken from the specimens is measured. Through multiple regression analysis, the authors propose a simplified method by which to evaluate the influence of each factor on segregation and thus obtain the non-uniform quality of concrete in actual RC structures. For the purpose of evaluating long-term durability performance, accelerated carbonation tests are executed. Further, a comparison of the regression analysis with the durability index proposed by JSCE is carried out. From these studies, it is shown that the proposed method can be used for the quantitative evaluation of material qualities in RC structures and their durability performance.

KEYWORDS: *Segregation, durability, porosity, cover concrete, carbonation*

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1. INTRODUCTION

Sustainable development in the 21st century depends on infrastructure that retains its performance over the long term. In order to construct such a durable and reliable infrastructure, it is necessary to evaluate the full life cycle cost and benefits of each structure as well as the initial cost of construction. On the other hand, for an already deteriorated structure, a rational maintenance and repair plan needs to be implemented in accordance with the condition of the structure. From this perspective, it is essential to understand material qualities and structural performance in advance of construction work in light of the expected environmental and load conditions during the structure's service life.

Here, it has to be remembered that material qualities specified at the design stage cannot always be assured in all domains of a structure since actually achieved material qualities are dependent on construction methods and the property of the fresh concrete. This causes difficulty in forecasting structural performance. As one way to overcome such uncertainties, the application of self-compacting concrete has been already proposed [1]. Self-compacting concrete may overcome the uncertainties associated with human error and concrete segregation, providing better guarantee over the uniformity of on-site concrete mixtures. This has been proven experimentally by showing the coefficients of variation of compressive strength of core specimens taken from a structure and small standard specimens are almost the same [2].

On the other hand, if we consider in-service concrete structures made of relatively high water-to-cement ratio concrete, it is to be expected that the quality of the concrete will differ with location. In particular, the durability of a structure is dependent on the quality of the cover concrete, which is strongly affected by concrete segregation. In the latest JSCE concrete specifications, quality differences between test-pieces and actual structural concrete can be taken into account by introducing a partial safety factor. It has not been demonstrated, however, how to determine the value of this safety factor in various cases. There is therefore a need to quantify the concrete quality achieved in a structure for any given set of construction methods, structural dimensions, and concrete materials.

The construction of a concrete structure involves many processes, including placing formwork and reinforcement, concrete casting, compaction, jointing of concrete sections, surface finishing, and curing. In each process, an initial defect may cause a reduction in structural performance due to various interactions among construction methods, material properties, structural details, and human error (Fig.1). In this research, human error and accidental factors, which are difficult to treat in a deterministic approach, are not taken into account. Neither are defects that affect the appearance of a structure, i.e., bending of reinforcement, deformation of formwork, insufficient cover depth caused by mislaying concrete spacers, honeycombing on the concrete surface due to insufficient compaction, cold joints due to inadequate treatment of construction joints, and so on. Regarding these initial defects, many investigations have been carried out in the past from the viewpoint of a quantitative evaluation of human error in the construction process [3], probabilistic approaches based on statistics [4][5], the effect of construction joints on durability performance [6][7], and evaluation methods for initial defects in a structure using non-destructive tests [18][19].

This research focuses on a quantitative evaluation of non-uniformities in the quality of concrete materials, otherwise known as material segregation. Material segregation as studied here is defined as the following phenomenon: "constituent materials (water, binders, and aggregate) move independently due to gravitational force after casting, and this leads to variations in constituent ratios and the quality of materials in the space domain". This type of segregation has been the focus

Construction process	Initial defect	Primary causes
Placing formwork & reinforcement	Insufficient concrete cover Early-age cracking	Mislaying of concrete spacer, miss-arrangement of reinforcement, deformation of formwork
Casting	Settling shrinkage cracks Plastic cracks Segregation (aggregate)	Too much bleeding, early-age drying, delayed bleeding, casting height, property of fresh concrete
Compaction	Segregation (water and aggregate) Honeycomb, surface voids Channeling, surface exfoliation	Excessive compaction Insufficient compaction
Jointing concrete	Cold joint	Insufficient treatment of joint
Surface finishing	Settling shrinkage cracks	Insufficient tapping

Fig.1 Initial defects during construction

of much attention in the past. Some examples are a quantification of bleeding phenomena based on the fundamental modeling of constituent particles [8], measurement of water-to-powder-ratio distribution in a plain concrete structure without a reinforcement, quality evaluation of cover concrete through tests of strength, mass transport and carbonation depth [11][12][13], and measurement of cover concrete rigidity of specimens that have different structural details and properties of fresh concrete [14][15]. However, no rational and systematic method of evaluating the quality of concrete as it varies due to various factors in the reinforced concrete has yet been presented.

In the research, specimens imitating a real structure were prepared with three categorized parameters: structural details, construction method, and materials. To evaluate material segregation, macroscopic indexes measured during the experiments were examined by multiple regression analysis, and then the relative influence of each factor was extracted. Furthermore, by implementing accelerated carbonation tests and comparing measured experimental data with the durability index specified in the JSCE durability assessment proposal [3], several case studies of durability performance evaluation for RC structures suffering material segregation were executed.

2 EXPERIMENT FOR MEASUREMENT OF MATERIAL SEGREGATION

2.1 Outline of experiment

As already mentioned, the authors focused on three main influences on segregation: structural details, construction method, and properties of the fresh concrete (Fig.2). These conditions set up based on the JSCE standard construction specification, reports of past research, and typical design specifications in actual construction.

Concrete structures are built up from a variety of constituent members, including columns, beams, slabs, walls, and box culverts, and it would be difficult to prepare specimens representing all these shapes. In this research, only column and beam specimens were made as typical structural members. Most concrete structures can be categorized into two broad construction categories, i.e., the orientation of the main reinforcement is perpendicular or parallel to the concrete casting direction. A

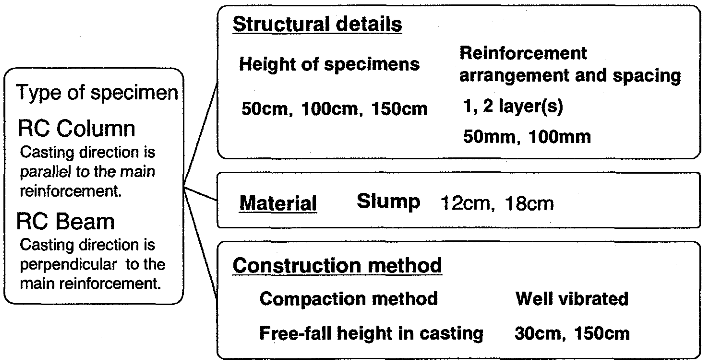


Fig.2 Experimental conditions

beam specimen represents the perpendicular direction, whereas a column specimen represents the parallel direction. For these two types of the specimens, concrete porosity was measured as a macroscopic index of the material segregation. In addition, accelerated carbonation tests were also implemented in order to examine the long-term durability. The number of total core sample specimens was 824. Using statistical methods, the influences of all factors on segregation were evaluated quantitatively.

2.2 Definition of experimental specifications

Regarding structural details, the size and reinforcement arrangement of the specimens were taken as parameters (Fig.3 and Fig.4). Structural sizes were specified with the aim of evaluating the effect of the specimen height as,

Beams: 60cm×60cm× 50cm and 60cm×60cm×100cm
Columns: 60cm×60cm×100cm and 60cm×60cm×200cm

Next, the spacing of the reinforcement and the number of reinforcement layers were varied as controlling parameters. In the JSCE code, the minimum spacing of reinforcement is specified as 40mm, and it is generally specified as approximately 100mm in actual design plans. Following these conditions, in the experiment, two spacing variations were used in the column specimens. As for the beam specimens, only one spacing arrangement was specified, since the effect of spacing is not likely to be dominant considering the location of the core sampling zones and the reinforcement.

Beams: 50mm
Columns: 50mm and 100mm

The number of reinforcement layer(s) was specified as follows.

Beams: 1 and 2 layer(s), spacing of each layer is 50mm
Columns: 1 and 2 layer(s), spacing of each layer is same as that of reinforcement

Cover depth was set constant at about 60 [mm] in this research.

With regard to the parameter reflecting the properties of the flesh concrete, two slump values were

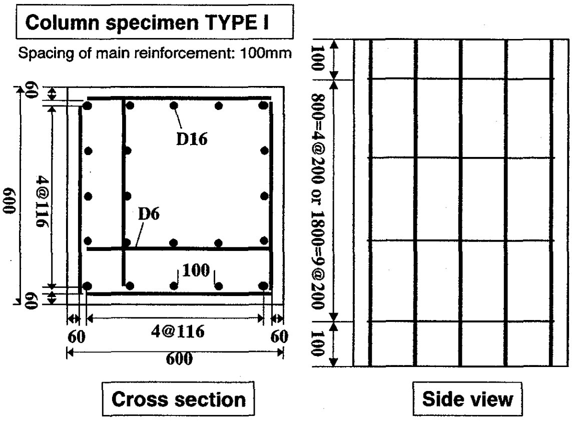


Fig.3 Structural details of beam specimens

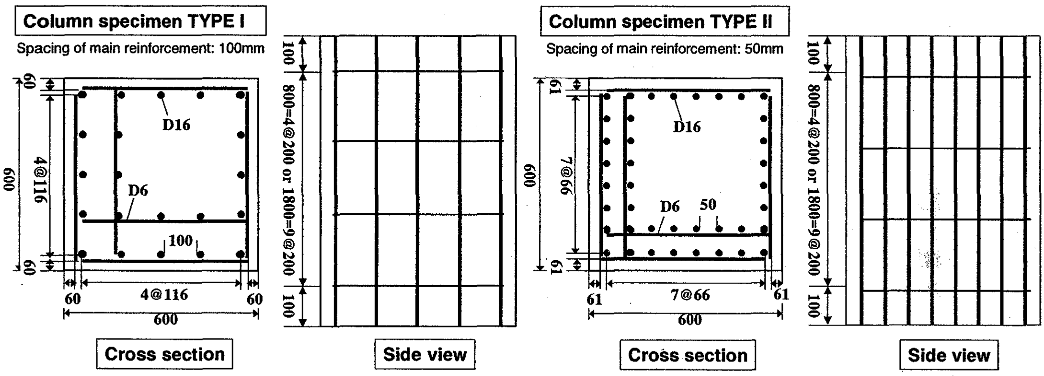


Fig.4 Structural details of column specimens

specified: 12 [cm] and 18 [cm]. Table 1 shows the specifications of the ready-mixed concrete (corresponding to JIS A 5308) used in the experiments. Both concretes have the same mix proportion. The designed strength was 24 [N/mm^2], and the maximum size of the coarse aggregate was 20 [mm]. The 18 [cm] slump value was achieved using a plasticizer.

A number of past investigations have attempted to evaluate the effect of construction methods on segregation by changing compaction methods [15][16][19]. Compaction condition can be specified by controlling the time of compaction, however, it can be expected that the efficiency of vibration energy transfer will be dependent on the skill of workers as well as the performance of the internal vibrator. Since other experimental parameters are independent of human skill, the reliability and stability of the experimental results can be ensured by considering only the well-vibrated condition. Therefore, in this research, a single compaction method was applied. Table 2 shows the compaction method for each specimen. The vibrating location and time were determined based on the JSCE construction specifications and past research so as to assure sufficient compaction. As a future direction, the authors understand that segregation phenomena for any arbitrary compaction method and energy of vibration should be studied, though this evaluation is not necessary when using self-compacting concrete.

As for the free-fall height in casting, 30 [cm] and 150 [cm] were examined for beam specimens since the JSCE code prescribes that the vertical separation between the pump outlet and the casting

Table 1 Mix proportion of concrete

Strength (N/mm^2)	W/C (%)	Slump value (cm)	Air content (%)	Unit weight (kg/m^3)			
				Water	Cement	Sand	Gravel
24	58.9	12.0 or 18.0	4.0	162	275	816	1056

Table 2 Compaction method for each specimen

Height of specimen	Compaction method
50cm	Vibrating at heights 30cm and 50cm
100cm	Vibrating at heights 30cm, 60cm, and 100cm
200cm	Vibrating at heights 30cm, 60cm, 100cm, 130cm, 160cm, and 200cm

For each layer, concrete was vibrated for 15 seconds at 5 points (center and corners, corresponding to a 30cm vibrating space).

surface of the concrete should be less than 150[cm]. On the other hand, for column specimens, considering casting conditions in the experiment, the casting height was specified as 150 [cm]. When casting the 200 cm column, the casting height was 200 [cm].

2.3 Experimental procedure

Core samples were taken from the structural specimens, and then porosity was measured as an index expressing material segregation. In addition, accelerated carbonation tests were executed in order to examine the long-term durability. The experimental procedure was as follows:

1. Casting of beam and column specimens (with slump value and air content measurements for each batch, and preparation of standard test pieces ($\phi 10 \times 20$cm))
2. Wet curing by sprinkling with water twice a day for three days
3. Stripping of steel formwork after 4 days
4. Core sampling from the specimens
5. Core samples and test pieces cured in water for 17 days

(For porosity measurements)

6. After submerged water curing, core samples cut into small pieces using a wet concrete cutter
7. Measurement of wet weight of samples in air and sample weight in water
8. Oven-drying (110℃) of samples for one day
9. Measurement of dry weight of samples

(For accelerated carbonation tests)

10. After submerged water curing, all surfaces other than one exposure surface were sealed. Specimens kept for 7 days in a controlled chamber where the concentration of CO_2 gas (15%), temperature (25℃), and relative humidity (55%RH) were kept constant.
11. Phenolphthalein solution sprayed on split specimens
12. Measurement of carbonation depth using digital planimeter

While the beam and column structural specimen were being cast, cylindrical specimens of radius 10cm and height 20cm were also made in order to obtain the standard properties of the concrete.

These were used to evaluate the quality variations of the core specimens. Core sampling locations are shown in Fig.5. For both beams and columns, four core specimens were taken from the top surface, side (upper), side (center), and side (bottom) of the structures. Three of the samples were used for porosity measurements, and one was used for the accelerated carbonation test. In the carbonation test for beam specimens, core samples were taken from the bottom surface instead of the bottom of one side. The specimens for porosity measurement were sliced into 1 cm thick disks: portions at 0-1cm, 1-2cm, and 4-5cm from the surface were prepared as shown in Fig.6. Where there were two layers of reinforcement, the midsection at 9-10cm was taken out as well. The reason for slicing in this manner is that, in the past research, more bleeding water was found to be present in concrete nearer the formwork (mainly within 2cm of the surface) [11]. This results in high ratios of water-to-cement and volume of cement paste in the concrete. On the other hand, it has been reported that the quality of inside concrete (specifically, deeper than 4cm from the surface) is almost same as that of the original concrete [12]. However, if reinforcement is present inside the concrete as specified in this experiment, it can be expected that the concrete properties may vary due to the influence of the reinforcement. Therefore, concrete near the inside reinforcement was extracted for measurements of material segregation.

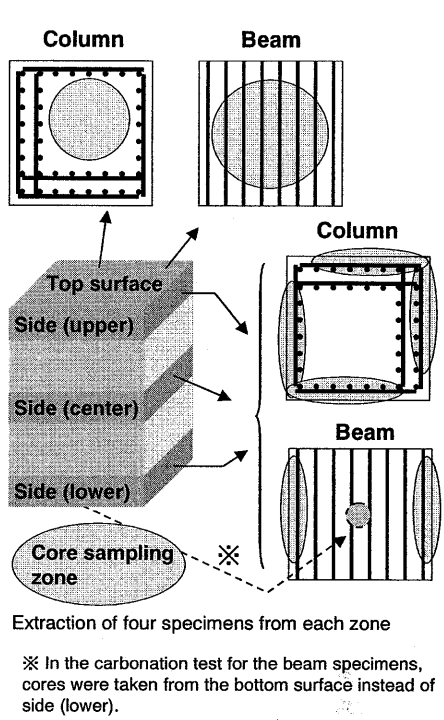


Fig.5 Core sampling zones in column and beam specimens

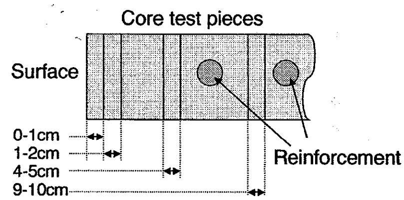


Fig.6 Test pieces sliced from the surface

The porosity of the specimens, ϕ, was obtained by the following equation:

$$\phi = \frac{W^a_{wet} - W^a_{dry}}{W^a_{wet} - W^w_{wet}} \quad (1)$$

where, W^a_{wet} ; weight of wet sample in air, W^w_{wet} ; weight of sample in water, W^a_{dry} ; oven-dried weight of sample in 110℃ chamber.

In the accelerated carbonation test, specimens were kept in a controlled chamber where the concentration of CO_2 gas (15%), temperature (25℃), and relative humidity (55%RH) were kept constant. To measure the carbonation depth, a picture of the split surface was first taken with a digital camera. The average carbonation depth was then obtained by tracing the picture with a digital planimeter.

3 QUANTITATIVE EVALUATION OF SEGREGATION BY MEASURED POROSITY

3.1 General

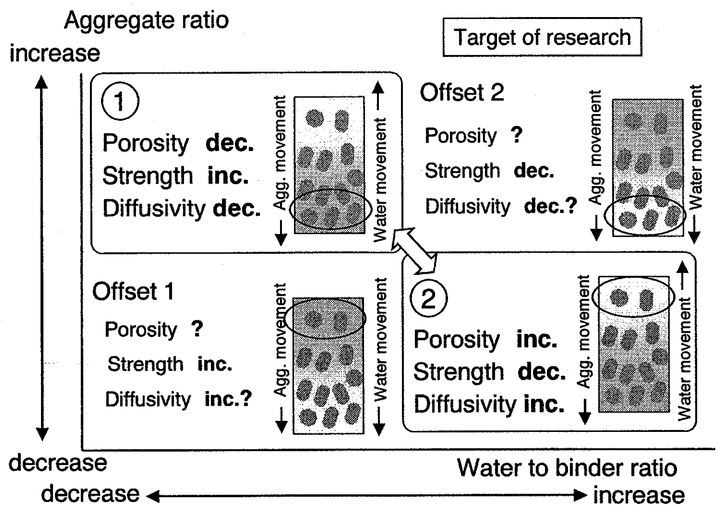


Fig.7 Relationship between ratio of constituent materials and achieved material properties

In quantifying the segregation phenomenon by multiple regression analysis, it is necessary to define a dependent variable and independent variables. In this research, porosity is taken to be a property that expresses the degree of segregation, and is defined as the dependent variable. The porosity does not always represent the discrepancy in quality from the standard specimen with accuracy. However, it primarily depends on the ratio of paste matrix to total volume and the water-to-binder-ratio of the paste matrix. Thus, it is thought to be one possible index for evaluating material segregation. Figure 7 schematically shows the relationship between porosity as obtained in the experiment and the ratio of constituent materials in the concrete. One expected form of segregation consists of vertical movements of water and aggregate. In this case, these components will move in opposite directions due to differences in specific gravity. That is to say, when water moves up and aggregate sinks, the porosity toward the bottom decreases (category ① in Fig.7). This is seen as an improvement in material quality in the form of higher strength and lower permeability. On the other hand, toward the top, the increase in volume and water-to-binder ratio of the paste matrix mean that the porosity increases (category ② in Fig.7). In this case, lower strength and higher permeability are the result. In such cases, segregation can be expressed by the porosity index alone. However, when both the ratio of aggregate and water-to-binder ratio simultaneously increase or decrease, segregation cannot be evaluated using porosity only. Even though the measured porosity may be the same, the strength and permeability may be higher or lower than the designed values. This results from offsets in the variations of cement paste volume and water-to-binder ratio (category offset 1 and 2 in Fig.7). Still, the corresponding real situation is really limited to unlikely cases, such as where vertical movement of the aggregate is impeded by aggregate blockage between reinforcing bars. So, assuming that the segregation phenomenon under given experimental conditions can be mostly represented by conditions ① and ② in Fig.7, porosity alone was used to evaluate the non-uniform quality of the concrete.

In the analysis explained in this section, the following two assumptions are made:

- The standard specimens have the prescribed mix proportions.
- The porosity of concrete is the summation of the porosity of the cement paste and the volume of air. Air content is given as the measured value for each batch before concrete casting.

3.2 Multiple regression analysis

Table 3 List of independent variables in the multiple regression analysis

Independent variable	Property
Core sampling location	Qualitative
Distance from surface	Qualitative
Height of specimen	Quantitative
Slump value	Quantitative
Casting height	Quantitative
Spacing of reinforcement	Quantitative
No. of reinforcement layer(s)	Quantitative

Table 4 Dummy variables for qualitative independent variables

Independent variable	Dummy variable			
		Loc. 1	Loc.2	Loc.3
Core sampling location	Top surface	1	0	0
	Side (upper)	0	1	0
	Side (center)	0	0	1
	Side (lower)	0	0	0
		Dis. 1	Dis. 2	Dis. 3
Distance from surface	0-1 cm	1	0	0
	1-2 cm	0	1	0
	4-5 cm	0	0	1
	9-10 cm	0	0	0

The absolute value of measured porosity cannot be used directly as the dependent variable in multiple regression analysis, since multiple batches of concrete were cast in the experiment and the concrete quality (especially, air content) of each batch was slightly different. Thus, the normalized porosity difference Z defined by the following equation was applied:

$$Z = \frac{(\mu_s - A) - (\mu - A)}{(\mu - A)} = \frac{\mu_s - \mu}{\mu - A} \tag{2}$$

where, μ_s: measured porosity in the experiment, μ: porosity of the standard specimen, A: air content measured before casting.

Looking at the dependent variables, there is a mix of qualitative variables and quantitative variables: the former are those with no explicit values, whereas measured values of the latter can be directly used in the regression analysis. Here, core sampling location and distance from the surface were treated as qualitative variables, while height of specimen, slump value, casting height, spacing of reinforcement, and number of reinforcement layers were considered quantitative variables (Table

Table 5 Result of multiple regression analysis for the whole beam specimen

Independent variable	Regression coefficient	F value	P value	Standard error	Accuracy	
Loc. 2	24.30	60.88	0.0000	3.114	Coefficient of determination	0.6116
Loc. 1	23.02	54.63	0.0000	3.114	Adjusted coefficient of determination	0.5776
Loc. 3	16.30	27.39	0.0000	3.114		
Dis. 1	15.07	7.094	0.0089	5.656	Multiple correlation coefficient	0.7820
No. of layer(s)	5.741	5.273	0.0235	2.500		
Casting height	0.03542	3.303	0.0718	0.01949		
Slump value	0.7727	2.202	0.1406	0.5207		
Constant	-38.21	21.16	0.0000	8.308		

3). In a multiple regression analysis, qualitative variables can be converted into quantitative variables by adopting dummy variables (Table 4). For example, when a specimen was cored from the top surface, the dummy variable "value of Loc.1" is taken to be 1.0, and other variables are 0.0. A similar rule was applied to other cases.

The multiple regression analysis was based on the least squares method. In evaluating the significance of the dependent variables, forward-backward stepwise selection was applied, and variables with an F value of less than 2.0 were rejected. In general, the F value is obtained as the square of (regression coefficient)/(standard error of regression coefficient). Regarding the judgment of significance, the adjusted coefficient of determination R_s was used. It can be obtained as,

$$R_s = 1 - \frac{n-1}{n-p-1}\left(1 - R^2\right) \tag{3}$$

where, n: the number of samples, p; the number of dependent variables, R; multiple correlation coefficient.

3.3 Results of multiple regression analysis

(1) Analytical results for the whole beam structure

Firstly, multiple regression analysis was carried out for each specimen. Table 5 shows the analytical results for the whole beam structure. The adjusted coefficient of determination is 0.5776. This means that about 58% of the porosity variation throughout the structure can be explained by the defined independent variables. Focusing on the F value expressing the influence of the independent variables on the dependent variable, the overall trends can be summarized as follows:

- Distance from surface

Only dummy variable Dis.1 is selected, whereas other dummy variables are excluded. That is to say, material quality in the 0-1cm zone from the surface differs by the greatest margin from the designed mix, while the quality of inside concrete does not show a significant difference.

- Core sampling zone

The F values of Loc.1 and 2 are relatively large. At the top surface and at the side (upper), the rising bleed water and sinking aggregate cause the ratio of cement paste and the water-to-cement ratio to become larger. This mechanism causes a porosity increase in these areas. Further, the analysis

Table 6 Result of multiple regression analysis for the whole column specimen

Independent Variable	Regression coefficient	F value	P value	Standard error	Accuracy	
Loc. 2	19.51	78.52	0.0000	3.088	Coefficient of determination	0.6547
Dis. 1	20.07	44.93	0.0000	2.993	Adjusted coefficient of determination	0.6280
Loc. 1	19.39	39.43	0.0000	3.087		
Loc. 3	13.52	37.23	0.0000	2.216	Multiple correlation coefficient	0.8091
Slump value	0.6926	3.999	0.0477	0.3465		
Height of specimen	-0.06406	2.347	0.1280	0.04181		
Spacing of reinforcement	0.4880	2.096	0.1501	0.3370		
Constant	-18.20	3.065	0.0824	10.39		

indicates an F value several percent larger at the side (upper) than at the top surface. From this result, it is inferred that the contribution of the rising bleed water along the formwork is more prominent. Comparing the side (upper) with the side (center), the degree of segregation in the center side is smaller: the F value of Loc.3 is half of that of Loc.2. This result means that half way up the side of the specimen the decrease in paste ratio due to the sinking aggregate cancels the increase in water-to-cement ratio caused by bleed water. This discussion demonstrates that the analytical results reasonably well describe the segregation phenomenon, with the trend as already reported in past research [9][10]: the bleed water ascends along the formwork, and at the mid-point the trend of sinking aggregate is discernible.

- Number of reinforcement layer(s)

The coefficient of this factor is positive. This means that the reinforcement is an obstacle to aggregate movement, so it results in a porosity increase.

- Slump value and casting height

The F values of both factors are about 2~3. Compared with other factors, their influence on the regression equation are not significant. Since both coefficients are positive, material non-uniformity will be greater as the slump value and casting height increase. Roughly speaking, a comparison of regression coefficients indicates that an increase of 100 cm in casting height is almost equal to a slump value that is 5cm greater from the viewpoint of its effect on segregation.

This discussion simply confirms the trends of material segregation pointed out in past research, and little new qualitative knowledge is elucidated. However, the authors note that they have succeeded in a quantitative evaluation of the various factors affecting segregation.

(2) Analytical results for the whole column structure

Next, the results of multiple regression analysis for the column specimens are discussed. Table 6 gives a summary of the results. The adjusted coefficient of determination in this case is 0.6280. As in the previous section, the discussion of the results is summarized for each independent value.

- Distance from surface and core sampling location

As in the case of the beam specimens, these two factors have considerable influence on segregation. The values of these coefficients indicate that the same phenomenon occurs as with beam specimens, i.e., aggregate sinks, while bleed water moves up along the formwork. On the other hand, in contrast with the beam specimens, the porosity closest to the surface is obviously higher than elsewhere (the F value of Loc.1 in the column specimen is quite significant), whereas the F value of coefficients representing the core-sampling location is smaller than for beam specimens. This result suggests that reinforcement arranged near the formwork blocks the horizontal movement of aggregate, so the ratio of paste matrix increases near the concrete surface.

- Height of specimen

The F value for this factor is the largest of the quantitative dependent variables. This means that, of all the variables, the height of the specimen most affects segregation. Since the regression coefficient is negative, the deviation in porosity becomes smaller (less segregation occurs) as the specimen becomes higher. The reason for this may be that as the height of the specimen increases, porosity decreases due to consolidation of cement paste. This point will be discussed in more detail in the subsequent analysis for each core sampling location.

- Spacing of the reinforcement

Instinctively, one would expect the porosity to increase with narrower reinforcement spacing, since the ratio of paste should increase in the cover concrete because the aggregate is blocked. However, the analytical results indicate to the contrary: the coefficient shows a positive value, which means that porosity increases as the spacing of the reinforcement increases. This can be understood as follows. At the measuring point, the vertical reinforcement can restrict only the horizontal movement of aggregate. Compared with the vertical movement of aggregate during concrete casting, however this horizontal movement would be quasi-static, so blockage of aggregate by the reinforcement is unlikely to occur in the given experimental conditions. It can be also said that the total amount of horizontal water movement would be larger with less reinforcement (wider spacing), since the defined spacing is large enough compared with the maximum size of the aggregate.

(3) Multiple regression analysis for each core-sampling location

In the discussion above, regression equations to express segregation were obtained for each specimen. However, the multiple regression analysis cannot be said to be a strict treatment without distinguishing the core sampling locations, since the independent variables for each location affect segregation in different ways. For example, in the beam specimens, the influence of the number of reinforcement layers low on the side where the reinforcement exist will be different from that at the other locations where no reinforcement is arranged. In addition, the height of the specimen will aggravate segregation at the top, whereas it will decrease porosity due to consolidation of cement paste at the bottom. Thus, in this section, the multiple regression analysis for each location is applied to the beam and column specimens.

Figures 8 and 9 show the analytical results for each location on each specimen. These figures show the adjusted coefficient of determination, the factors with most influence, and their F value and sign. A plus sign represents a parameter that increases porosity, and minus sign means a parameter that decreases porosity.

Firstly, the beam specimens are considered. At the lower sides, no significant equation can be obtained: the adjusted coefficient of determination is 0.27. This would be due to the offset as shown in Fig.7. That is to say, the transverse reinforcement cause blockage of the aggregate, which leads to a decrease in cement paste content, whereas the water-to-powder ratio increases due to the bleed water. These two effects, i.e., the decrease in cement paste and increase in water-to-powder ratio, cancel out in terms of porosity variation. Thus, porosity alone cannot explain the segregation phenomenon at the bottom of the specimens. Regarding the other three locations, significant

Top Surface

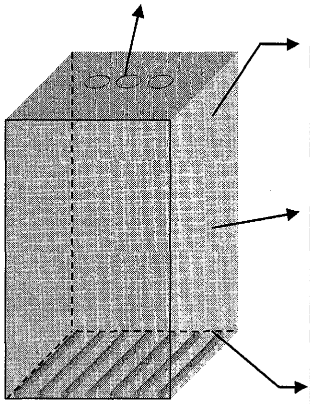
$R^2 = 59.0\%$

	F-values	Trend
1 Distance from the surface(0-1cm)	27.5	+
2 Casting height	8.71	+
3 Number of rebar layers	6.97	+
4 Height of specimen	5.65	−

NOTE)

R^2: Adjusted coefficient of determination

Plus sign : Porosity increasing
Minus sign : Porosity decreasing



Side (upper)

$R^2 = 77.0\%$

	F-values	Trend
1 Distance from surface(0-1cm)	90.3	+
2 Slump	8.24	+
3 Casting height	2.53	+

Side (center)

$R^2 = 55.9\%$

	F-values	Trend
1 Distance from surface(0-1cm)	29.0	+
2 Slump	3.89	+
3 Number of rebar layers	2.51	+

Side (lower)

$R^2 = 27.0\%$

	F-values	Trend
1 Number of rebar layers	6.86	+
2 Slump	5.65	+

Fig.8 Results of multiple regression analysis for each core sampling location (beam specimen)

Top surface

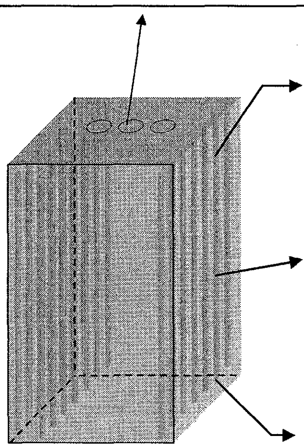
$R^2 = 77.6\%$

	F-values	Trend
1 Distance from surface (0-1cm)	40.9	+
2 Height of specimen	10.9	+
3 Spacing of reinforcement	2.80	−

NOTE)

R^2: Adjusted coefficient of determination

Plus sign : Porosity increasing
Minus sign : Porosity decreasing



Side (upper)

$R^2 = 69.8\%$

	F-values	Trend
1 Distance from surface (0-1cm)	90.3	+
2 Distance from surface (4-5cm)	3.95	+

Side (center)

$R^2 = 67.2\%$

	F-values	Trend
1 Distance from surface (0-1cm)	55.9	+
2 Number of rebar layers	9.02	+
3 Spacing of reinforcement	8.48	+
4 Slump	5.47	+

Side (lower)

$R^2 = 71.0\%$

	F-values	Trend
1 Height of specimen	55.8	−
2 Distance from surface (0-1cm)	27.0	+
3 Spacing of reinforcement	19.0	+

Fig.9 Results of multiple regression analysis for each core sampling location (column specimen)

coefficients are obtained. Therefore, a discussion of the phenomenon at the top, side (upper), and side (center) are presented.

In all locations, the results show that porosity variations in the region 0-1cm from the surface are most significant. Since other parameters related to location are excluded, this verifies that the quality of the concrete at the surface differs significantly from that of the standard specimen. Here, focusing on the influence of the surface region (0-1cm) for each location, the F value at the side (upper) is more than three times larger than that at the top and side (center). This result implies that there is more bleed water near the formwork than at the top. That is to say, there must be two modes of water movement: one is the horizontal movement of bleed water, which ascends along the formwork, and the other is the bleed water that moves up directly. From these analytical results, the contribution of the bleed water ascending along the formwork is clearly more significant.

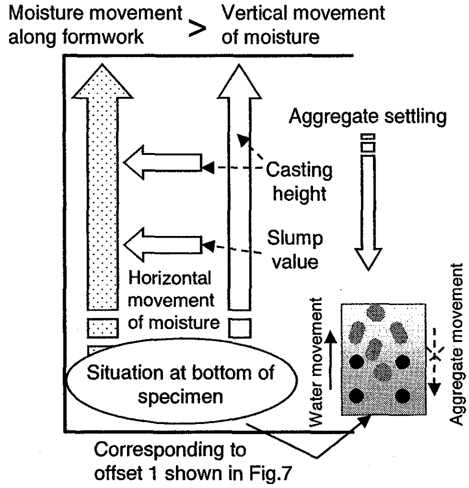


Fig.10 Schematic representation of material segregation in the beam specimen

Near the top of the beam, segregation is affected by the height of the specimen. As a specimen height increases, segregation becomes worse. The effect of slump value can be isolated at the side (upper) and side (center), which means slump promotes the horizontal movement of bleed water. Regarding the number of reinforcement layers, an effect is found at the top and side (center), whereas there is none at the side (upper). It is difficult to determine the reasons for this from the obtained results alone; however, it suggests that segregation caused by reinforcement low in the beam can affect material quality even at the top. At the top surface, the coefficient for specimen height is negative, contrary to expectations. This result represents a porosity decrease as the height of the specimen is increased. One possible mechanism for this would be the reduction in bleed water at the top surface due to interactions between ascending bleed water and sinking aggregate around the middle of the specimen. However, it cannot be concluded whether a reduction in porosity occurs as a result of this condition, because reliable results could not be obtained. The above discussed results are schematically shown in Fig.10.

Next, the column specimens are analyzed. In the multiple regression analysis, high correlation was obtained for all locations (with adjusted coefficients of determination ranging from 0.67 to 0.78). As with the beam specimens, the independent variable related to distance from the surface (0-1cm) is the factor with most influence on segregation at the top, side (upper), and side (center). In particular, the F value at the side (upper) is the highest, which means the contribution of ascending bleed water along the formwork after horizontal movement is quite significant, just as in the case of beam specimens.

At the side (lower), specimen height yields the highest F value. Since the coefficient is negative, as the specimen becomes higher, the porosity decreases due to consolidation of the paste matrix. On the other hand, at the top, a higher specimen leads to increased porosity due to the large amount of bleed water.

In all the domains except for the side (upper), the reinforcement spacing appears as an influential factor on segregation. From the middle to the bottom, its sign is positive, whereas at the top surface it is minus. The reasons for this are as follows: in the lower regions of the column, bleed water moves horizontally from inside the concrete toward the formwork due to consolidation of the cement paste. When the spacing of reinforcement is larger, i.e., the obstacles to such movement are reduced, the porosity of the cover concrete increases. Comparing the F value of reinforcement at the

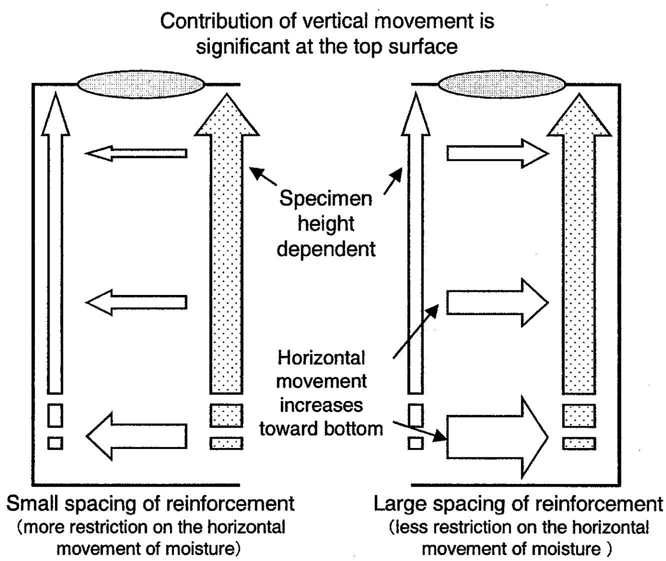


Fig.11 Schematic representation of material segregation in the column specimen

bottom with that half way up, the value at the bottom is larger. This result implicitly indicates that the amount of horizontal movement is larger at the bottom of the specimens. On the other hand, as to the reason why the coefficient of reinforcement spacing is negative at the top surface, it is inferred that the amount of water moving vertically is less due to the reduced reinforcement.

This discussion is limited in scope to the case of the quasi-static movements of aggregate and water, and also to the range of the experimental conditions, such as the 50 mm minimum spacing of reinforcement. The authors understand that in order to clarify the general relationship between material segregation and reinforcement spacing (such as during the dynamic movement of aggregate as seen in casting with smaller spacing), further research and analysis is needed. Figure 11 schematically shows the results obtained on the basis of the above discussions.

4 ACCELERATED CARBONATION TEST

4.1 General

In this section, in order to directly measure structural durability performance, accelerated carbonation tests on core samples taken from the structural specimens are described. We attempt to quantify the progresses of carbonation, which varies depending on location.

4.2 Experimental results

The measured carbonation depth of the core specimens was transformed into a variation from the value for the small standard specimen (ϕ10×20[cm]) made from each batch of concrete. Figures 12 and 13 show the experimental results for the beam and column specimens, respectively. It is shown that, at the bottom of both beam and column specimens, owing to the consolidation of cement paste, the rate of carbonation progress is almost same, or less than that of the standard specimen. However, at other locations, the depth of carbonation is approximately 30% deeper at the maximum compared with the standard concrete having the specified mix proportion, although the variations is dependent

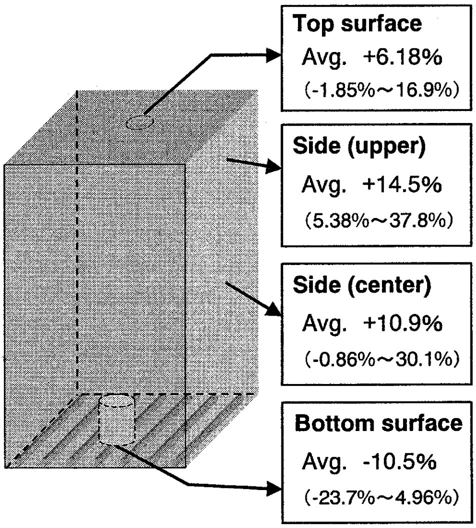


Fig.12 Variation of carbonation depth between standard specimen and core samples (beam specimen)

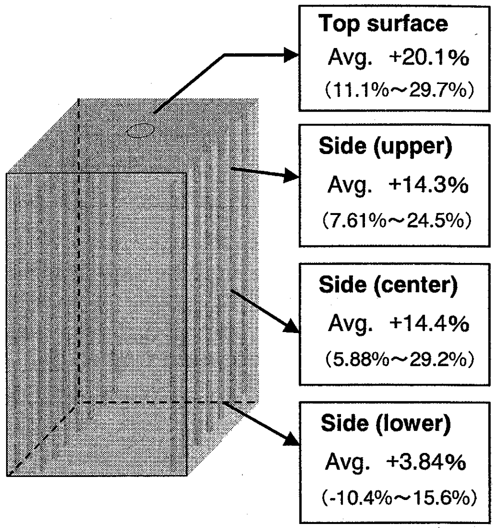


Fig.13 Variation of carbonation depth between standard specimen and core samples (column specimen)

on experimental conditions. This result suggests that this deteriorated quality should be considered at the design stage, since the carbonation rate of structural concrete is faster than that of the standard specimens. That is to say, if a partial safety factor is applied, a value of 1.3 should be chosen.

In this research, only accelerated carbonation tests were implemented. Other aspects of durability, such as chloride migration and steel-corrosion, also need to be studied. However, it may be expected that the same trend would be seen, since these phenomenon are strongly affected by mass transport inside the concrete just as carbonation is.

4.3 Multiple regression analysis on the carbonation progress

By carrying out a multiple regression analysis on the results, the influence of each factor was quantified. Table 7 shows the results of this multiple regression analysis. The analytical method and criteria for choosing significant variables were the same as in the previous analysis described in section 3. The adjusted coefficients of determination for the beam and column specimens are 0.8009 and 0.6547, respectively. For both specimens, the dependent variables related to the sampling location and material property are significant. Comparing the values of the regression coefficient, the variation in carbonation depth increases with location in the following: side (upper), top surface, and side (center). This holds for both beam and column specimens. In the analysis of measured porosity, exactly the same trend is found, and the results obtained in this section are consistent with the earlier analysis. For example, in case of beam specimens, the depth of carbonation is 25% greater at the side (upper), 18% at the top surface, and 17% at the side (center) than the standard specimen of the specified mix proportion. It is also found that the coefficient related to material property, i.e., the slump value, affects carbonation progress. The value of the regression coefficient means that the depth of carbonation increases by 3% as the slump value increases by 1cm.

Table 7 Result of multiple regression analysis for accelerated carbonation test

Beam specimen Adjusted coefficient of determination: 0.7499			Column specimen Adjusted coefficient of determination: 0.6547		
Independent variable	Regression coefficient	F value	Independent variable	Regression coefficient	F value
Loc. 2	25.35	67.53	Loc. 2	21.45	27.43
Loc. 1	18.18	34.73	Loc. 3	17.80	19.27
Loc. 3	16.94	28.82	Loc. 1	21.21	18.31
Slump value	3.082	27.94	Slump value	3.006	12.10
Constant	-51.06	59.28	Constant	-25.92	2.423

5 COMPARISON OF REGRESSION ANALYSIS WITH JSCE DURABILITY INDEX

5.1 General scheme

A durability design proposal was first issued by the JSCE in 1989, with a modified proposal published in 1995. The original and crucial point of this proposal concerning durability engineering was that it numerically scored overall durability performance in terms of a number of fictitious durability points, against which the durability of a concrete structures could be objectively ranked. This new concept made clear for the first time that the evaluation of the limit state for the durability of concrete structures would be the focus of development. In the design proposal, the factors influencing durability performance were categorized into material, structural detailing, and construction factors. The linear summation of these durability points, taking into account each influence factor, gives an estimate of the durability index of a structure T_p. If the durability point T_p exceeds the environmental index S_p, obtained from the environmental conditions and the maintenance-free period, the durability of the structure is assured within the framework. On the other hand, in the multiple regression analysis discussed in previous sections, the influencing factors were quantified by the measured porosity of the structural specimens. Therefore, in this chapter, we aim to compare the obtained regression equation with the durability index specified in the JSCE durability design proposal.

Since the multiple regression equation expresses the porosity variation as a linear summation of each factor, it cannot be directly compared with the durability index. Thus, the authors first estimate the mix proportion of specimens using a simplified method, and then carry out a multiple regression analysis for estimated water-to-cement ratio. Through this process, the variation in terms of the achieved water-to-cement ratio can be specified. On the other hand, although the durability index is non-dimensional value, the variation in water-to-cement ratio corresponding to a change in each influencing factor can be obtained by an appropriate conversion as described in the next section. By means of these treatments, it becomes possible to compare both methods in the same frame.

5.2 Simplified method for estimating water-to-cement ratio using measured porosity

The measurements made in the experiment were specific gravity and porosity. The authors attempted to estimate unknown values in the mix proportion, such as air content and amount of cement, water, and aggregate from these two known values. However, the sensitivity of specific gravity on the estimated value was found to be quite large; if the value of specific gravity varies by ±0.01, which corresponds to an error of about 1 [g] in the experiment, the estimated

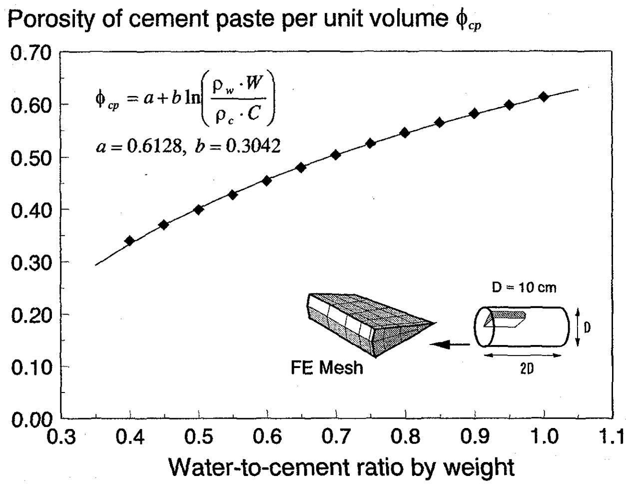


Fig.14 Equation for porosity evaluation of paste matrix obtained by thermo-hygro system [20]

water-to-cement ratio varies by 25%~45%. Thus, we determined it would be difficult to estimate the mix proportion using both specific gravity and porosity, and instead proposed a simplified method for estimating the mix proportion using only porosity.

The porosity obtained in the experiment, ϕ, can be described by the following equation:

$$\phi = A + \frac{\rho_g \cdot p_w}{1 + p_w} G + \phi_{cp}(W + C) \tag{3}$$

where, A: air content [m^3/m^3], G: volume of aggregate [m^3/m^3], W: volume of water [m^3/m^3], C: volume of cement [m^3/m^3], ρ_g: density of aggregate under saturated surface-dry conditions [kg/m^3], p_w: adsorption rate of aggregate, and ϕ_{cp}: porosity of cement paste. The second term on the right-hand side of the equation represents the amount of water driven out by heating in an oven. The porosity of the cement paste was estimated by an integrated thermo-hygro system [20]. All of the input values in the analysis corresponded to the experimental conditions, including the size and shape of the specimen, curing method, and environmental conditions. Figure 14 shows the mesh layout and the results of the analysis. Based on the analytical results, the following function was adopted to express the porosity variation depending on water-to-cement ratio:

$$\phi_{cp} = a + b\ln\left(\frac{\rho_w \cdot W}{\rho_c \cdot C}\right) \tag{4}$$
$$a = 0.6128,\ b = 0.3042$$

where, ρ_c: density of cement and ρ_w: density of water. In addition, the summation of the constituent volume should satisfy the relationship as,

$$A + G + W + C = 1.0 \tag{5}$$

This discussion leads to two relationships among A, G, W, and C. However, two relationships for 4 unknowns cannot yield a solution. Therefore, in making the estimation, air content A and volume of aggregate G are assumed to be constant. This assumption implies that air content and volume of aggregate are independent of structural details, material properties, and the construction method. However, if the ratio of paste matrix varies due to significant segregation of the aggregate, such a simplified method fails to yield a correct solution. Although a direct way to measure the water-to-cement ratio and aggregate ratio of hardened concrete by chemical analysis would be most

Table 8 Estimated water-to-cement-ratio of small standard specimens

Lot No.	1	2	3	4	5	6	7
Average porosity	0.1848	0.1843	0.1837	0.1655	0.1652	0.1689	0.1734
Air content	5.7%	5.8%	5.5%	3.0%	4.2%	3.6%	4.2%
Estimated W/C	0.584	0.570	0.585	0.611	0.598	0.601	0.593
Error	-0.005	-0.019	-0.004	0.022	0.009	0.012	0.004

appropriate, here the water-to-cement ratio was estimated by the simplified method, mainly focusing on the segregation of water and aggregate. As a first approximation, this treatment would appear to be valid, since the variations in water and aggregate ratios would be most significant under the experimental conditions. Under this assumption, according to the Eq. (3), the estimated porosity is a controlling factor on the estimation of water-to-powder ratio. In other words, the estimation accuracy depends on the Eq. (4) shown in Fig.14. From the various verifications described in the past [20], the relationship between water-to-cement ratio and porosity under the given conditions should be able to give reasonable solutions with adequate accuracy.

The proposed method was verified by using the measured porosity of the cylindrical standard specimens (Table.8). As shown in the table, the water-to-cement ratio was estimated within $\pm 2\%$ accuracy.

5.3 Calculation of durability index

The multiple regression analysis was executed once again for the water-to-cement ratio at each core sampling location, as estimated by the simplified method described in the previous section. From this procedure, the following regression equation was obtained:

$$W/C = \sum_{i=1}^{n} a_i X_i \qquad \frac{\partial (W/C)}{\partial X_i} = a_i \tag{6}$$

where, X_i: independent variables and a_i: regression coefficients. As shown in Eq.(6), the regression coefficient reflects the fluctuation in water-to-cement ratio per unit amount of each factor. In order to directly compare the regression analysis with the durability index T_p in the JSCE durability specifications [3], the equation below was used.

$$\frac{\partial (W/C)}{\partial X_i} = \frac{\partial T_p}{\partial X_i} \cdot \frac{\partial (W/C)}{\partial T_p} \tag{7}$$

According to Eq. (7), the durability index can be converted into values corresponding to the regression coefficient. By using Eqs. (6) and (7), the results obtained in the experiment were quantitatively verified against the durability index, which was determined on the bases of engineering expertise.

The following factors specified in the durability specifications [3] relate to the experimental conditions:

(a) Factors related to materials and structural detail
Compactability (flowability)

$$\begin{gathered} 2(E_{10}-10)+E_{11}(1-E_{10}/30) \\ E_{11}=(10-8/A_{21})+(5-F_{32}^2)+A_{22} \end{gathered} \tag{8}$$

where, E_{10}: slump value [cm], E_{11}: coefficient representing the effect of the shape/size of a member on concrete compactability, A_{21}: minimum transverse size of a member, F_{32}: height of casting lift,

and A_{22} : constant representing the change in size of the cross section.
Compactability (resistance to segregation)

$$5-E_{12}(E_{10})^2 \tag{9}$$

where, E_{12}: coefficient representing the resistance to segregation.

(b) Factors related to construction method
Casting

$$2(1.5-F_{33}) \tag{10}$$

where, F_{33} is free-fall height during casting [m].

(c) Factors related to structural detail
Spacing and number of layers of reinforcement

$$15\left(1-\sqrt{2A_{50}}/A_{51}\right) \tag{11}$$

where, A_{50}: number of layers of reinforcement and A_{51}: spacing of reinforcement divided by the maximum size of aggregate.

In order to use Eq. (7), it is necessary to obtain the sensitivity of durability index T_p in terms of the variation in water-to-cement ratio. This can be calculated using the following index, which represents the rigidness of concrete:

$$55-E_2 \tag{12}$$

where, E_2: water-to-cement ratio (%). From the Eq. (12), the sensitivity term can be obtained as,

$$\frac{\partial(W/C)}{\partial T_p}=-1.0 \tag{13}$$

Tables 9 and 10 show the results of the multiple regression analysis and the durability index, respectively. Surveying the overall results, it is worthy of note that the order of the two sets of estimated values is almost the same. That is to say, the results derived here from experiment quantitatively prove the validity of the durability index, which was determined only based on engineering experience and expertise because of a dearth of quantitative knowledge in the late 1980's.

However, several areas of difference can be seen between the two estimates. In particular, identical scores are given to all locations within a structure by the JSCE durability design proposal, whereas multiple regression analysis is able to distinguish the different governing factors at each location and fully takes into account the interrelationships among these factors. Further, some of the factors show opposite sign in the experimental work, which means the qualitative trends are contradictory. For example, if the structural details specified in the experiment are applied to the JSCE proposal, a larger slump value is found to cause less segregation. This is because, in the evaluation function in the JSCE proposal, a larger slump value leads to higher flowability rather than less resistance to segregation. On the other hand, in the obtained experimental results, as the slump value increases, the horizontal movement of water becomes significant, i.e., the slump value is isolated as a factor causing material segregation. With regard to the spacing of the reinforcement, as in the discussion in section 3, the water-to-cement ratio increases with greater spacing of reinforcement. The authors understand that further work using more combinations of influencing factors is needed to clarify these outstanding questions.

This comparison demonstrates the applicability of multiple regression analysis as well as the validity of the durability index. The proposed method is a means of improving the accuracy of the durability design framework. However, as noted previously, the simplified method of estimating the

Table 9 Variation in water-to-cement ratio per unit of influential factors
(Results obtained by experiment)

	Specimen height	Casting height	Slump value	Reinforcement spacing	No. of reinforcement layer(s)
	50, 100, 200	30, 150	12, 18	5, 10	1, 2
Unit	cm	cm	cm	cm	number
Beam top surface	-0.216	0.0633	-	-	2.69
Beam side (upper)	-	0.0783	2.45	-	-
Beam side (center)	-	-	2.23	-	10.1
Column top surface	0.0597	-	-	-0.540	-
Column side (upper)	-	-	-	-	-
Column side (center)	-	-	0.696	1.21	8.47
Column side (lower)	-0.165	-	-	1.49	-

Table 10 Variation of water-to-cement ratio per unit of influential factors
(Results obtained by the JSCE durability assessment proposal [3])

	Specimen height	Casting height	Slump value	Reinforcement spacing	No. of reinforcement layer(s)
	50, 100, 200	30, 150	12, 18	5, 10	1, 2
Unit	cm	cm	cm	cm	number
Beam top surface	0.006~0.009	0.02	-0.17~-0.15		3.51
Beam side (upper)	0.006~0.009	0.02	-0.17~-0.15		3.51
Beam side (center)	0.006~0.009	0.02	-0.17~-0.15		3.51
Column top surface	0.012~0.018	0.02	-0.27~-0.17	-0.85~-1.2	1.76~3.51
Column side (upper)	0.012~0.018	0.02	-0.27~-0.17	-0.85~-1.2	1.76~3.51
Column side (center)	0.012~0.018	0.02	-0.27~-0.17	-0.85~-1.2	1.76~3.51
Column side (lower)	0.012~0.018	0.02	-0.27~-0.17	-0.85~-1.2	1.76~3.51

achieved mix proportion considers only the segregation of water and cement, which are thought to be most variable of the constituents. We recognize that, in future, it is necessary to improve the trustworthiness of the proposed method by considering the segregation of aggregate as well as that of water and cement paste.

6 CONCLUSION

In this research, beam and column specimens fabricated with different structural detailing, concrete, and construction methods were tested in order to quantify the non-uniform quality of concrete as obtained in a real structure. As a macroscopic index expressing concrete quality, the porosity of core samples taken from the structural specimens was measured. By performing statistical analysis, the mechanisms of segregation and the factors influencing it were quantified. Accelerated carbonation tests were used to show that the depth of carbonation is approximately 30% greater at maximum as compared with concrete having the actually specified mix proportion. This means that, when using ordinary concrete, even though good compaction may be assured, the safety factor representing the quality difference between structural concrete and small-sized specimens should be given a value of 1.3. In addition, through a statistical approach using a simplified estimation method for mix proportion, it was possible to compare the test results with the JSCE durability index. Generally speaking, the orders of both estimations were similar, so proving the validity of the JSCE durability design proposal. It was also shown that the proposed methodology can be used to make the durability design system more accurate and trustworthy.

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