Monitoring system for chloride content in concrete cover using Electromagnetic Wave and Impedance Methods

T. Mizobuchi
Hosei University, Tokyo, Japan

K. Yokozeki, K. Watanabe, M. Hiraishi & R. Ashizawa
Kajima Corporation, Tokyo, Japan

ABSTRACT: Reinforcement corrosion caused by the presence of chloride ions in the neighborhood of the re-bars has been identified as one of the major causes of deterioration of concrete structures. The chlorides could find their way to concrete either as part of constituent materials when sea sand is used, or, by gradual permeation and diffusion as in the case of marine structures, or, cases where deicing salts are used to melt away snow on highways, etc. Thus, determination of chloride content in a concrete structure is an important part of periodic nondestructive testing carried out for structures identified to be vulnerable to chloride induced reinforcement corrosion. In this report, the applicable monitoring system which is possible to estimate the distribution of chloride content included in cover concrete in the existing structures using electromagnetic wave method and impedance method which are non-destructive testing is reported.

1 INTRODUCTION

Reinforcement corrosion caused by the presence of chloride ions in the neighborhood of the re-bars has been identified as one of the major causes of deterioration of concrete structures. The chlorides could find their way to concrete either as part of constituent materials when sea sand is used, or, by gradual permeation and diffusion as in the case of marine structures, or, cases where deicing salts are used to melt away snow on highways, etc. Thus, determination of chloride content in a concrete structure is an important part of periodic nondestructive testing carried out for structures identified to be vulnerable to chloride induced reinforcement corrosion.

On the other hand, a definite understanding about any corrosion of reinforcement is very difficult unless corrosion induced cracks appear on the surface. Thus, in order to detect chloride-induced corrosion at an early stage, chloride content within concrete needs to be investigated using cores drawn from the RC structure, and carrying out chemical analysis. Now, drawing cores could be structurally unacceptable, damage the reinforcement and the repair could be aesthetically unappealing, only very limited sampling can actually be carried out. In addition, drawing cores to estimate the chloride content in concrete could not make it possible to study the changes in chloride content over time (at exactly the same place). On the other hand, it has been obtained from laboratory tests under limited conditions that chloride content within concrete has could be almost estimated by using electromagnetic waves as one of the non-destructive tests. However, as all specimens have be added sodium chloride during the mixing of concrete in the laboratory tests, the experiments have been not carried out to estimate chloride content using specimens permeated chlorides from the concrete surface after placing. Since experiments to estimate the chloride content in concrete using electromagnetic waves have been carried out to apply existing concrete structures to be a premise, the convenient measuring instrument that the frequency was fixed was used. However, it should be considered that excellence frequency may be changed by water content and chloride content in concrete. In case of the estimation of chloride content using the electromagnetic wave, though it is possible to estimate only average chloride content from the concrete surface to the reinforcing bar, it is not possible to estimate the distribution of chloride content from concrete surface to the reinforcing bar.

Furthermore, in our studies, experiments have been carried out to estimate moisture content and chloride content near concrete surface from resistance value and frequency of concrete using impedance method. From results of the experiments, the frequency band as maximum effective value has tended to be changed by chloride content and water content with age. Also, maximum effective value and frequency has tended to increase according as the measurement point was closer to the concrete surface. In addition, the maximum effective value has tended to increase according to decrease average water content of the concrete. By utilizing results of our studies obtained until now, it is possible that the system in which it is able to carry out the monitoring using these methods of non-destructive testing is developed in respect of grasping the distribution of the chloride content in cover concrete.

In this report, the applicable monitoring system which is possible to estimate the distribution of chloride content included in cover concrete in the existing structures using electromagnetic wave method and impedance method which are non-destructive testing is reported.

2 ESTIMATION OF CHLORIDE CONTENT USING ELECTROMAGNETIC WAVE

2.1 *Outline on measurement of chloride content in concrete using electromagnetic waves*

The dielectric constant of dry concrete varies in between 4 to 10, and that of wet concrete in the range of 10 to 20. Thus, the dielectric constant of concrete varies depending on the moisture content of concrete. As mentioned above, the dielectric constant is the same for both fresh water and seawater.

In this study, as shown in Figure 1, when the distance to the reflecting surface, i.e. reinforcing bar, was known, it was detected that changes in the properties of the electromagnetic waves such as the dielectric constant are caused by differences in the properties of the intervening medium such as the moisture content, which in this case is concrete. Furthermore, it was also confirmed that changes of dielectric constant in the electromagnetic waves weren't caused by differences in the chloride content in concrete.

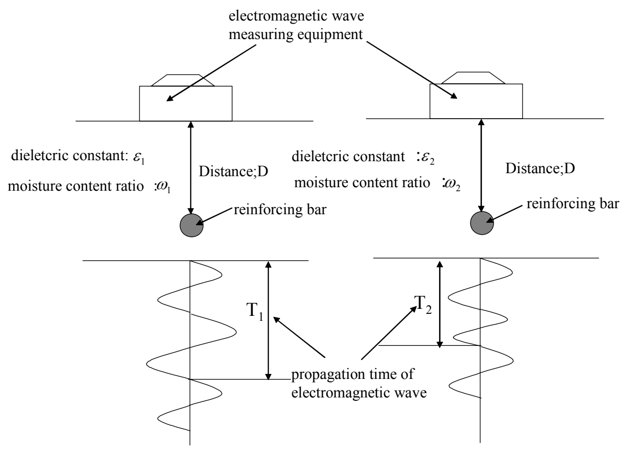

Figure 1. Concept of electromagnetic wave measurement.

As mentioned above, the conductivity is likely to vary considerably with the amount of chloride ions in concrete. That is to say, when the electrolyte like sodium chloride exists in the concrete, it seems to be changed the electrical properties such as conductivity in comparison with the concrete without the chloride ions. Furthermore, because the amount of electrolyte varies with the difference of chloride ions concentration, the amount of electrolyte also changes depending on the moisture content in the concrete.

In this study, therefore, it was detected that changes in reflected waveform of electromagnetic waves were caused by differences in chloride ions concentration and moisture content in the concrete.

2.2 *Method of investigation*

Experiments were carried out by dividing them into two steps. In the first step, experiment were carried out to chloride content in concrete from properties of electromagnetic wave waveforms measured using test specimens cast using varying chloride content. Further measurements for attenuation of the output waveforms and the dielectric constant were carried out over a period of 13 weeks, to study the changes in the moisture content in concrete over that period. As shown in Table 1, six types of test specimens in which the chloride content in the test specimens was varied from 0 kg/m^3 to 6 kg/m^3 in steps of 1 kg/m^3 were used to study.

In the second step, the specimens with the seal were made to penetrate in water of chloride ion concentration whose was 3% and 10% for about 3 months.

Table 1. Patterns of specimens.

Reinforced conrete	Plain concrete	Content of chloride (kg/m^3)
R-0	P-0	0.0
R-1	P-1	1.0
R-2	P-2	2.0
R-3	P-3	3.0
R-4	P-4	4.0
R-5	P-5	5.0
R-6	P-6	6.0

2.3 *Materials used and mix proportion*

Table 2 and Table 3 show the materials used and the mix proportion of concrete used in casting the test specimens.

2.4 *Specimens*

In the first step, as shown in Figure 2, two kinds of specimens, R and P, whose size were 100×100×400 mm were prepared. Specimens R contained one 16mm diameter deformed bar as shown, whereas specimens P did not contain any reinforcement.

In the second step, Specimens, whose size were 100×100×400 mm were prepared. The test specimens

Table 2. Details of materials used

Materials	Summary
Cement	Ordinary portland cement, density:3.16g/cm^3, fineness:3320cm^2/g
Fine aggregate	Hill sand, saturated surface-dry particle density: 2.62g/cm^3, fineness modulus:2.57
Coarse aggregate	Crushed stone, saturated surface-dry particle density: 2.65g/cm^3, solid content: 59.4%
Chemical admixture	Air-entraining and water reducing agent of Libin sulfonic acid compound, density: 1.25g/cm^3
	Air-entraining agent of denatuted rosinate-based anionic surface active agent

Table 3. Mix proportion of concrete

Maximum size of coase aggregate (mm)	Water to cement ratio (%)	Sand content (%)	Unit quantity (kg/m^3)				
			Water	Cement	Sand	Gravel	AEWRA
20	60.0	45.5	165	275	838	1015	0.96

NOTE; AEWRA: Air-entraining and water reducing agent

were sealed all other planes of the specimen to permeate chloride ions from a plane of the specimen.

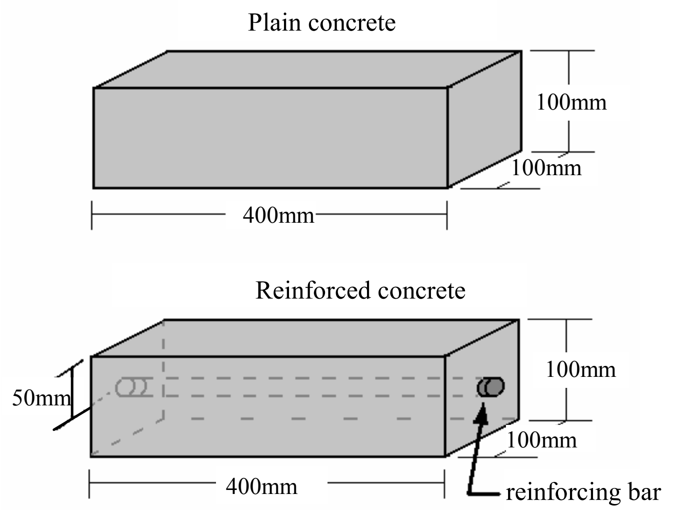

Figure 2. Specimens used electromagnetic wave measurement.

2.5 *Test methods*

One day after placement, the concrete specimens were removed and sealed in plastic bags so that the chloride ions in the specimens did not leach. The specimens were cured underwater for seven days, the moisture on the surface of the concrete specimens was wiped off thoroughly before carrying out any measurements. To study the change of the moisture content in concrete, the mass of the specimen, the temperature and humidity in the laboratory were measured during the electromagnetic wave measurement. For measurement of electromagnetic waves, an antenna of about 1.0 GHz with specifications as given in Table 4 was installed on the specimen. As shown Figure 3, the specimens were placed on a steel plate to intensify the reflected electromagnetic waves. As shown in Figure 4, the scale of the monitor was fixed at the level of the gain of the machine when the measurement was started, and the amplitude of the reflected electromagnetic wave estimated using that scale (Full scale = 100%).

Moreover, since the reflected wave from the reinforcement and the reflected wave from the steel plate are likely to interfere with the reflected wave in the case of R specimens, the reflected waveform of the P specimen was subtracted from the measured waveform of the R specimen. Thus, as shown in Figure 5, the effect of only the presence of the reinforcement in the case of R specimens could be independently studied.

Table 4. Specifications of electromagnetic wave measuring equipment.

Item	Specifications
Rader frequencies	1.0 GHz
Measurement method	Impuls method
Transmission voltage	17Vp-p (at load 50Ω)
Horizontal resolution	80 mm

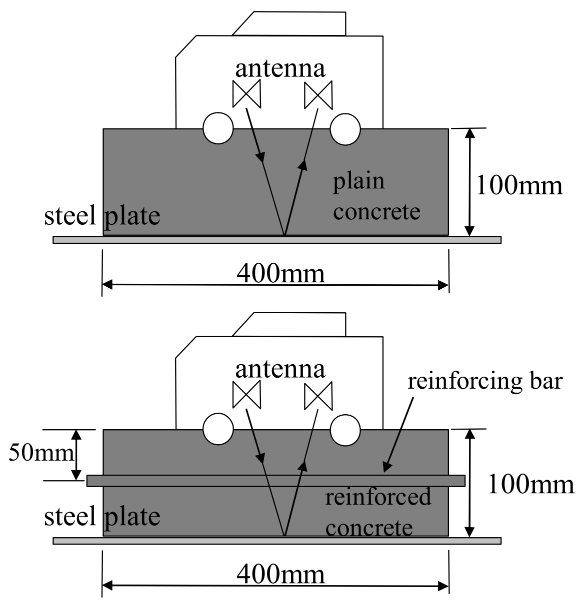

Figure 3. Measuring method.

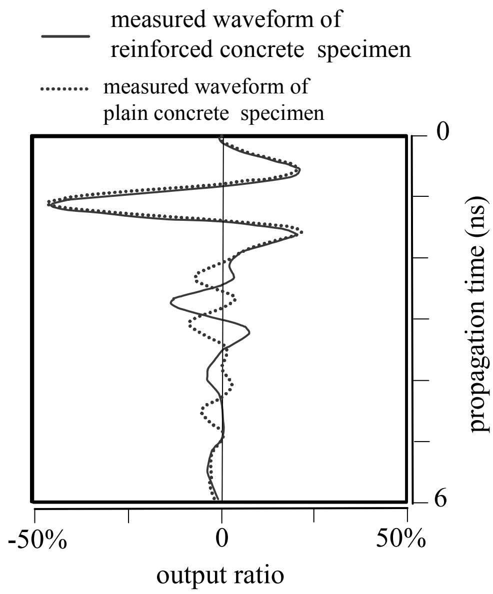

Figure 4. Effect of reinforcing bar in measured waveform.

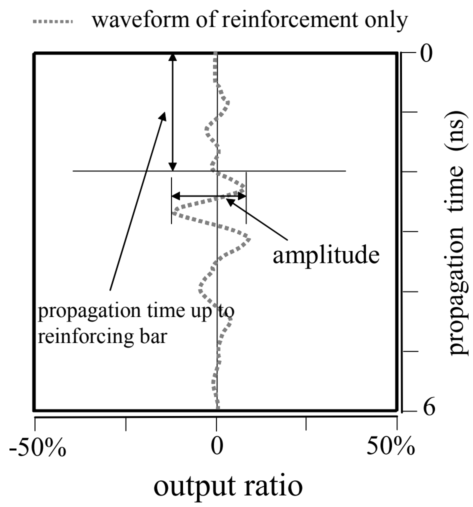

Figure 5. Example of waveform with subtraction.

2.6 *Test results and discussions*

This study confirmed that the amount of moisture in concrete affected the measured amplitude of electromagnetic waves, and this needs to be appropriately considered when making an estimate of the chloride content in concrete. In this study, the latter estimates have been carried out by making the estimates in two ways – without and with considering the effect of water content, and the results are shown in Figure 6 and Figure 7 respectively. The multiple regression coefficients for the cases when moisture content was neglected and was considered was found to be 0.69 and 0.87, respectively, clearly showing the improvement in the estimated values by considering the moisture content.

The above results show that the accuracy of estimation of content of chloride ions using electromagnetic wave was improved in cases when the effect of moisture content was considered. However, as shown in Figure 7, it seemed that the variations of the estimated values for the respective content of chloride ions were large. Thus, to investigate the cause of these variations in the estimated values, multiple regression analysis was carried out separately for each day of measurement, and the results are shown in Figure 8. The multiple regression coefficient was found to be 0.98, indicating substantially improved estimates. In addition, the multiple regression analysis considering amount of moisture in concrete was also carried out for each day of measurement. When the moisture was considered, the estimated values tended to approach closer to the actual values. However, in this method, test-specimens for calibration need to be always prepared, and the calibration needs to be carried out on the day of the measurement. Moreover, partial regression coefficients calculated using the multiple regression analysis for the respective day of the measurement are needed to estimate the content of chloride ions. Thus, this method for estimating the content of chloride ions using electromagnetic waves requires a lot of time and effort. Then, the following were compared: Estimates using all the data and using the data of the different days of measurement.

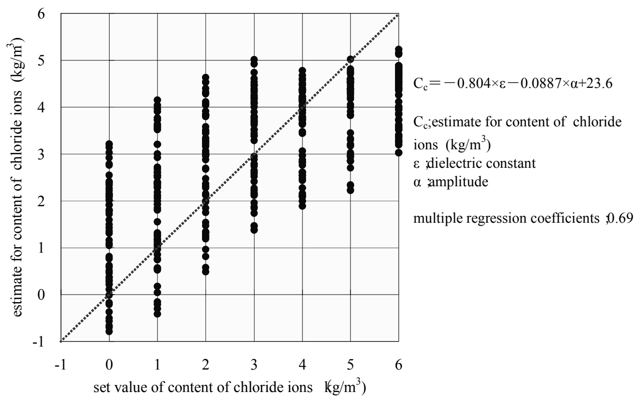

Figure 6. Estimate of chloride content without considering moisture.

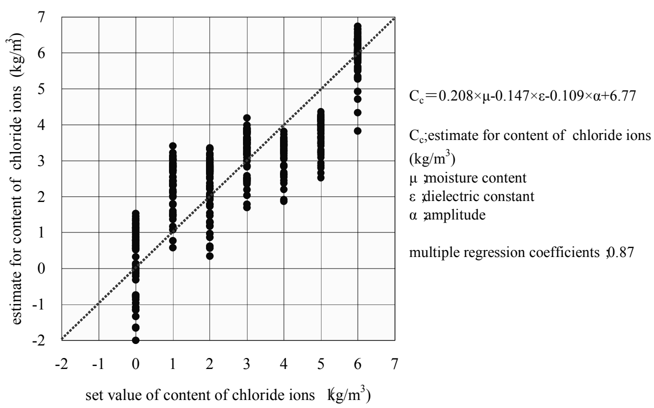

Figure 7. Estimate of chloride content with considering moisture.

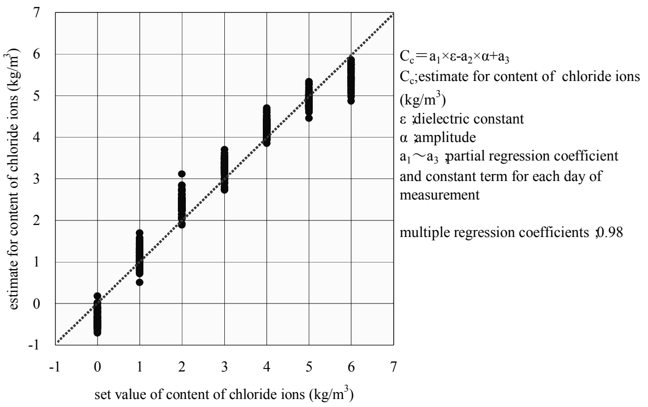

Figure 8. Estimate of chloride content for each day of measurement.

Figure 9 shows the results in the former case. Figure 10 shows the changes depending upon ages on temperature and humidity in the laboratory during the measurement. As shown in Figure 9, the estimated values tend to have negative slope. As shown in Figure 10, temperature and humidity in the laboratory also tended to have a negative slope as the measurements were carried out from the middle of August to the middle of November. It was proven that the changes of estimates shown Figure in 9 was similar to the changes of temperature in the laboratory shown in Figure 10. To consider this factor, multiple regression analysis was carried out again taking the temperature in the laboratory as an additional predictor variable.

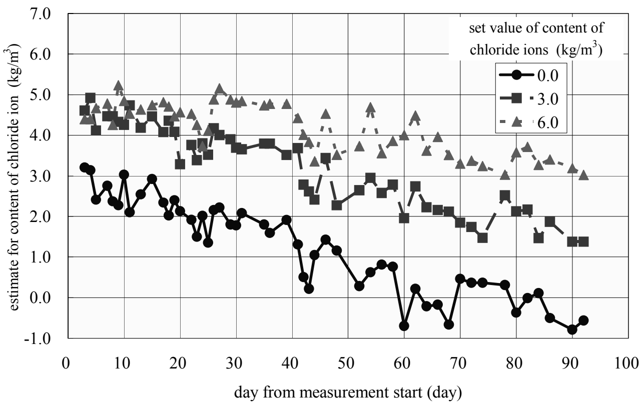

Figure 9. Changes of estimate of chloride content.

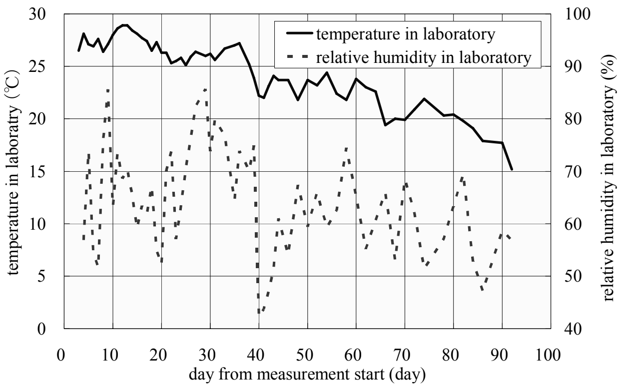

Figure 10. Change of temperature and relative humidity.

As shown in Figure 11, the multiple regression coefficients were 0.90 and the estimates were reasonably accurate. When the amount of moisture in concrete was considered, as shown in Figure 12, the regression coefficient was 0.94.

Figure 13 shows the example of the estimated result in the case when the content of chloride ions is 3.0kg/m^3. The result of multiple regression analysis not considering the effect of moisture content and the temperature at the time of measurement, had a negative slope, but when these factors are accounted for, the estimated values become quite close to the actual ones. Thus, it can be concluded that the content of chloride ions can be estimated with good accuracy from the amplitude values of electromagnetic waves, taking into account the effects of amount of moisture in concrete and air temperature.

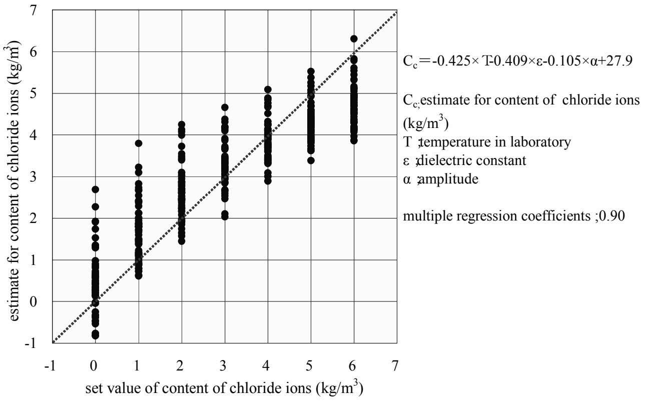

Figure 11. Estimate of chloride content with considering temperature

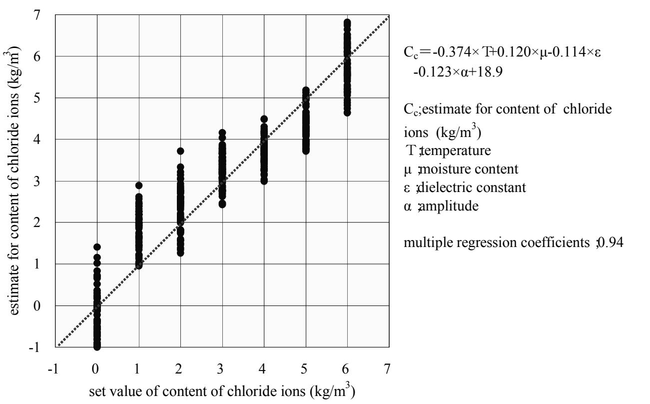

Figure 12. Estimate of chloride content with considering temperature and moisture content.

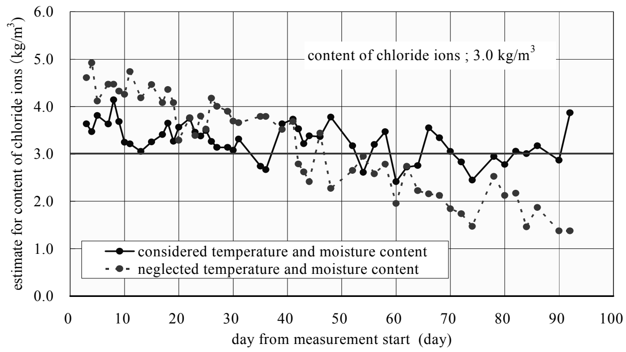

Figure 13. Effect of temperature and moisture content for chloride content.

From results of the experiments carried out in the laboratory, it was found that the content of chloride ions could be estimated with fairly good accuracy from the measurement of electromagnetic waves. When estimating the content of chloride ions, the dielectric constant, amplitude vales of reflected electromagnetic waves, amount of moisture in concrete and air temperature should be considered. Then, the content of chloride ions, C_c, as the criterion variable can be estimated by the multiple regressions analysis taking temperature in the laboratory T, amount of moisture in concrete μ, the dielectric constant ε and the amplitude value α as the predictor variables, using equation 1 below.

$$C_C = -0.374\times T + 0.120\times \mu - 0.114\times \varepsilon - 0.123\times \alpha + 18.9 \quad (\mathrm{kg/m^3}) \qquad (1)$$

Next, two cores were respectively drawn from one test specimen in order to analyze content of all chloride ions and content of soluble chloride ions within each specimen which respectively was penetrated in water of 3% and 10%chloride ion concentration. Figure 14 shows relationship between depth from the concrete surface and content of chloride ions.

In case when the content of chloride ions is estimated using electromagnetic waves, it is seemed that the content of chloride ions estimates the average content to object (steel plate laid under the test specimen in this experiment) reflected the electromagnetic waves from concrete surface. Then, Figure 15 shows respectively the average of content of all chloride ions and soluble chloride ions shown in Figure 14 and the content of chloride ions estimated using equation (1). In case where the specimen penetrated in water of 3% chloride ion concentration, the average of content of all chloride ions was about half content estimated and the average of content of soluble chloride ions was about 1/3 content estimated. On the other hand, in case where the specimen penetrated in water of 10% chloride ion concentration, the average of content of all chloride ions and soluble chloride ions were respectively 2.3kg/m^3 and 1.9kg/m^3, while the content of chloride ions estimated using equation (1) was 2.6kg/m^3. The content of chloride ions estimated using equation (1) was comparatively approximate to that of all chloride ions.

As mentioned above, in case where the specimen penetrated in water of 3% chloride ion concentration, the content of chloride ions estimated differed from the content of chloride ions measured. Because, though the chloride ions were permeated only to vicinity of 50mm depth from concrete surface, it was estimated that chloride ions permeated to 100mm depth from concrete surface. In case where the specimen penetrated in water of 10% chloride ion concentration, it seemed that the estimated content of chloride ions became comparatively similar for the average content of chloride ions measured, since the chloride ions permeated to vicinity of 80mm depth.

If it is assumed that the electromagnetic wave is not almost attenuated within not containing chloride ions, when the content of all chloride ions is averaged within permeating of chloride ions, the average content of chloride ions becomes 1.9kg/m^3 in case where the specimen penetrated in water of 3% chloride ion concentration and becomes 2.6 kg/m^3 in case where the specimen penetrated in water of 10% chloride ion concentration. Therefore, in both cases, the estimated content of chloride ions became similar for the average content of chloride ions measured. However, in actual structures, it is proven whether chloride ions have permeated in the neighborhood of the reinforcing bars. Therefore, the content of chloride ions estimated using electromagnetic waves may be estimated larger than that permeated in concrete, when the chloride ions have not permeated to the neighborhood of the reinforcing bars yet.

Therefore, in case of the estimation of chloride content using the electromagnetic wave, though it is possible to estimate only average chloride content from the concrete surface to the reinforcing bar, it is not possible to estimate the distribution of chloride content from concrete surface to the reinforcing bar.

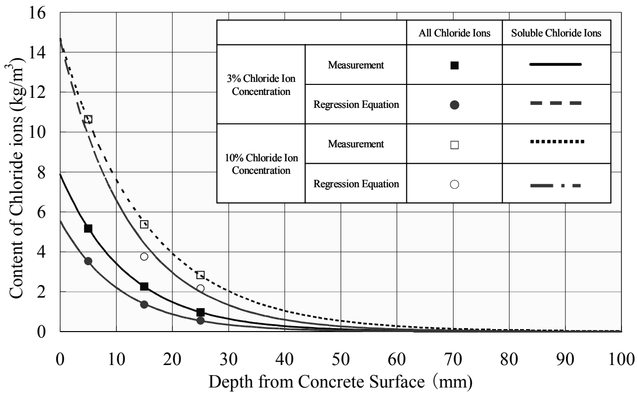

Figure 14. Distribution of Content of Chloride ions.

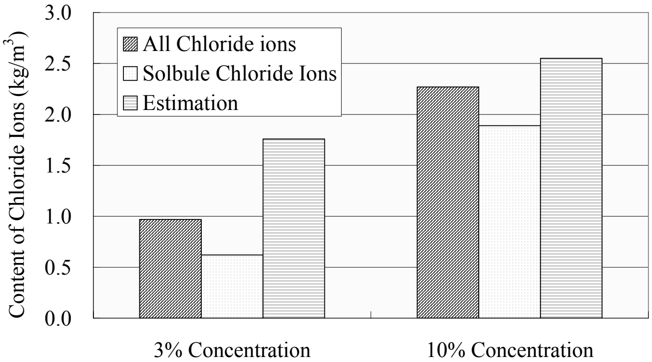

Figure 15. Comparison of Content of Chloride Ions.

3 ESTIMATION OF CHLORIDE CONTENT IN SURFACE DIVISION OF CONCRETE USING IMPEDANCE METHOD

3.1 *Outline on measurement of chloride content in concrete using impedance method*

In this study, as shown in Figure 16, alternating current was applied across one pair of the embedded silver electrode from the synthesizer and frequency (MHz) changed and effective values were read from the oscilloscope. The effective value shows the change of the amount of alternating current which passes in the concrete at the voltage difference (mV). The input waveform was made to be amplitude (2Vp-p) and frequency.

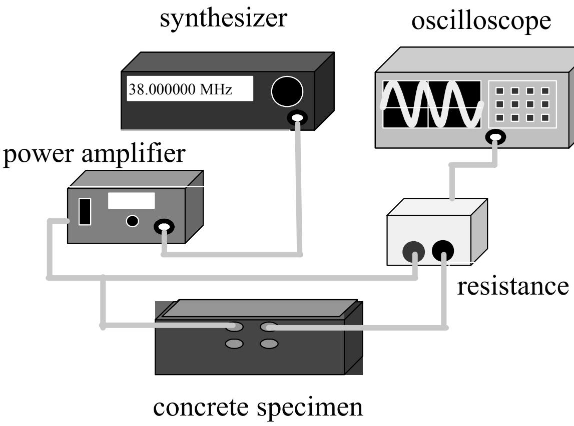

Figure 16. measuring circuit.

3.2 *Specimens*

As shown in Figure 17, specimen whose size was 100×100×400 mm was prepared. A reinforcing bar and silver electrodes were embedded in the specimen. As shown in Figure 17, the silver electrode was embedded from the surface to the position of 1cm and 5cm and each electrode was embedded in 4cm interval in the specimen. In the concrete surface, the silver electrode was fixed in insulating tape, insulation rubber and concrete weight. Table 5 shows the mix proportion of concrete used in casting the test specimens. As shown in Table 6, five types of test specimens in which the chloride content in the test specimens was varied from 0 kg/m^3 to 10 kg/m^3 were used to study.

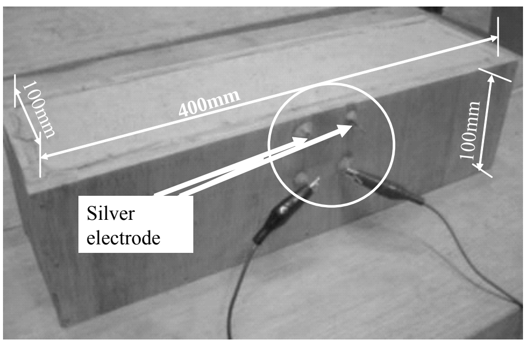

Figure 17. Specimen used measurement

Table 5. Mix proportion of concrete.

Slump (cm)	Air content (%)	Water to cemnt ratio	Sand content (%)	Unit quantity (kg/m^3)					
				Water	Cement	Sand	Gravel	AEWRA	AEA
12	4.5	60.0	45.4	173	347	798	961	1.08	0.0035

NOTE;AEWRA:Air-Entraining and Water Reducing Agent, AEA:Air-Entraining

Table 6. Patterns of specimens.

Type of specimen	Content of chlorids (kg/m^3)
A-0	0
A-1	3
A-2	5
A-3	7
A-4	10

3.3 *Test results and discussions*

Figure 17 shows results of the measurements using impedance method. As shown in Figure 17, the frequency that the maximum effective value was obtained decreased depending upon increasing in the distance from concrete surface. The maximum effective value was in the range from 37.0MHz to 38.5MHz on each case. Figure 18 shows relationship between the maximum effective values and the content of chloride ions. The maximum effective values tended to decrease with the increase in the content of chloride ions. The maximum effective value at the 1cm depth is larger than that at the 5cm depth. Figure 19 shows relationship between the effective values and the average moisture content. The effective values tended to increase with the decrease in the average moisture content.

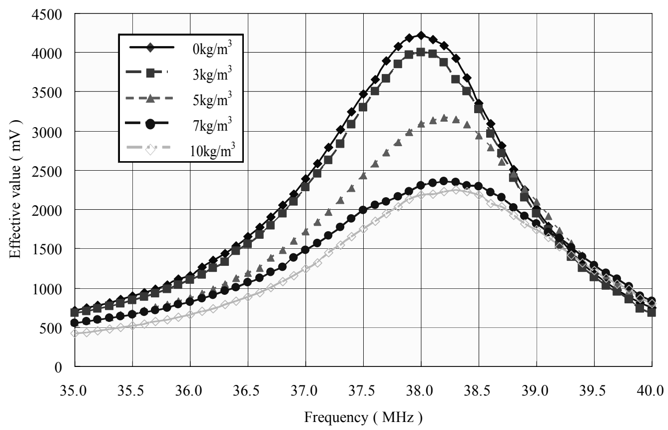

Figure 17. Relationship between frequency and effective value.

As mentioned above, it was made clear that the frequency band where the maximum effective value was obtained changed by chloride content and moisture content and that the maximum effective value and frequency tended to increase, as the measurement point was closer to the concrete surface. In addition, the maximum effective value tended to increase when average moisture content in the concrete specimens decreased. However, in present state, as the change of the maximum effective value is smaller than the change of chloride content and measurements of the maximum effective values greatly fluctuate in the concrete surface, it is necessary to pay attention that chloride content in concrete surface is quantitatively estimated using impedance method.

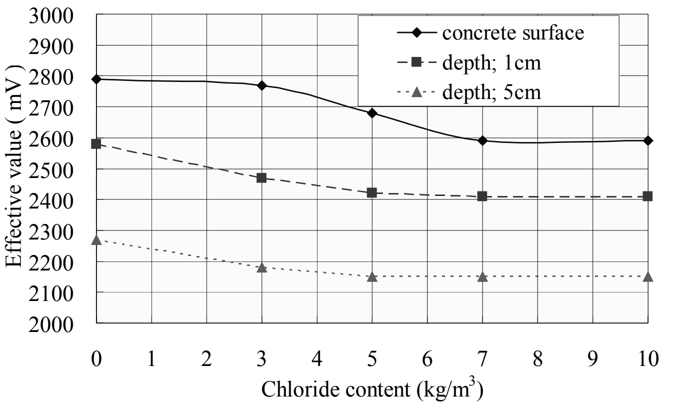

Figure 18. Relationship between chloride content and effective value.

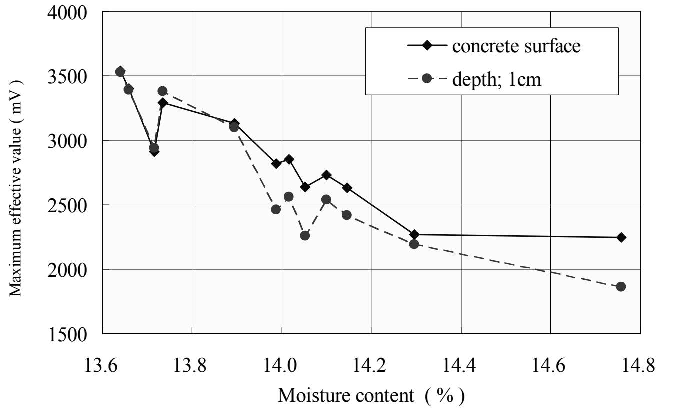

Figure 19. Relationship between moisture content and Maximum effective value.

4 MONITORING SYSTEM OF CHLORIDE CONTENT USING ELECTROMAGNETIC WAVE AND IMPEDANCE METHOD

As mentioned above, since the value estimated using the electromagnetic wave method is the average of chloride content from the concrete surface to the reinforcing bar, it is not possible to evaluate the distribution of chloride content. Therefore, chloride content has excessively been evaluated, when chloride content has not reached the reinforcing bar. In the meantime, if electrode used impedance method is not embedded at the depth beforehand determined, it will be not easy that chloride content in the position is estimated. Then, it seems to be possible that the chloride content in the reinforced concrete is estimated at the good accuracy by utilizing merits of each other and supplementing demerits of each other. The estimation method on distribution of chloride content in reinforced concrete is shown in the following.

First of all, in an object position, current resistance values are measured by installing the electrode in the concrete surface using the impedance method. For the current resistance values, chloride content of concrete surface division is estimated from the relationship between current resistance values and chloride content of concrete surface division on the basis of results gotten in laboratory tests. Next, the average chloride content from concrete surface to reinforcing bar is estimated using the electromagnetic wave method. Figure 20 shows the relationship between results from each measurement mentioned above.

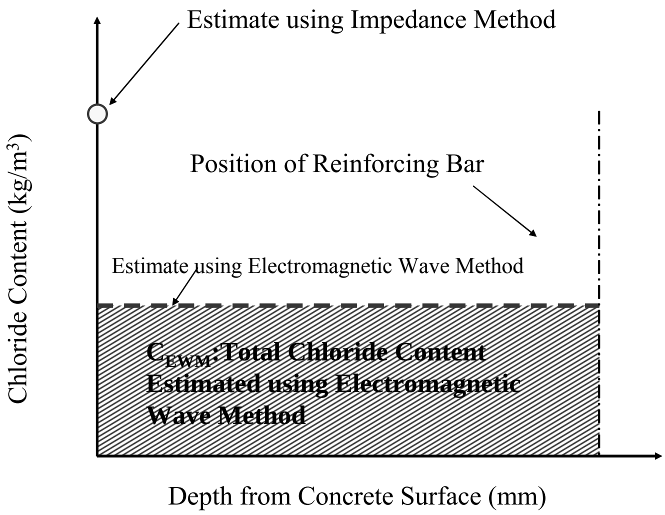

Figure 20. Estimate using electromagnetic wave and impedance method.

Generally, it is possible to obtain a permeation depth of chloride content using the Fick's law of diffusion. It is possible to obtain chloride content in an arbitrary position and in an arbitrary time by solving the differential equation showed equation (2).

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \quad (2)$$

$$C(x,t) = C_0 \left(1 - erf\left(\frac{x}{2\sqrt{D_c \cdot t}} \right) \right) \quad (3)$$

Where, C shows chloride content in an arbitrary position (x) and in an arbitrary time (t) (kg/m^3), D_c shows the value of diffusion coefficient of chloride ions into concrete (cm^2/year), C_0 shows chloride content at concrete surface (kg/m^3). *erf* (s) is error function defined as follow;

$$erf(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\eta^2} d\eta \quad (4)$$

Results from past studies give the value of diffusion coefficient of chloride ions into concrete in equation (4) in following equation.

$$log\ D_c = a\left(\frac{W}{C}\right)^2 + b\left(\frac{W}{C}\right) + c \tag{5}$$

Where, *a*, *b* and *c* are the coefficient determined by the type of cement and W/C is water cement ratio.

It is possible to calculate total chloride content permeated from concrete surface by using chloride content in concrete surface estimated using impedance method and the value of diffusion coefficient into concrete gotten from equation (5).

$$C(t)_{total} = \int C(x,t)dx \tag{6}$$

Where, $C(t)_{\text{total}}$ is total chloride content permeated from concrete surface in an arbitrary time.

As shown Figure 21, by determining permeation depth so that the total chloride content gotten in equation (6) may be equivalent to the average chloride content obtained by the electromagnetic wave method, it is possible to estimate the distribution of the chloride content from concrete surface.

At present, as shown Figure 22, in order to verify the distribution of chloride content estimated from both measurement results, chemical analysis to investigate chloride content within concrete is carried out with cores drawn from the specimens. The results of verification will be reported in the different opportunity.

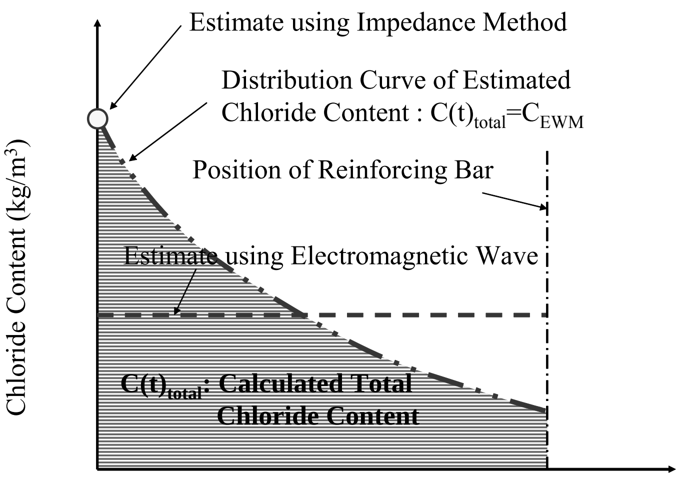

Figure 21. Estimate of distribution curve of chloride content.

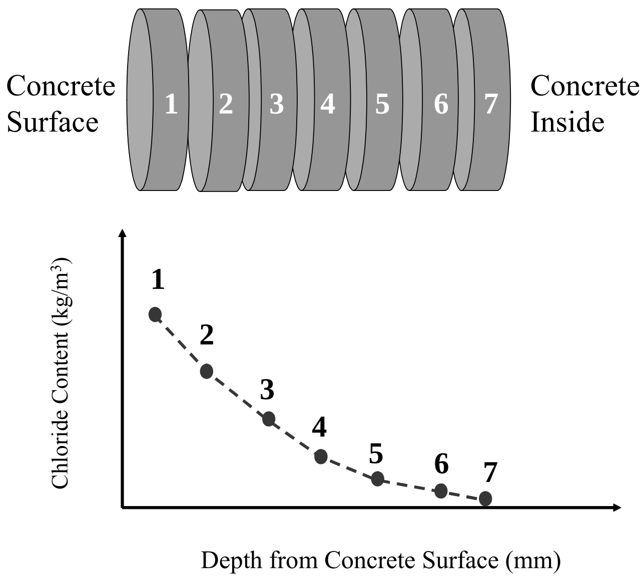

Figure 22. Verification of distribution of chloride content.

5 CONCLUSIONS

The present research examined the applicable monitoring system which is possible to estimate the distribution of chloride content included in cover con crete in the existing structures using electromagnetic wave method and impedance method which are non-destructive testing. The knowledge gained from this study can be outlined as follows.

(1) The content of chloride ions can be estimated with fairly good accuracy from the measurement of electromagnetic waves. The dielectric constant, amplitude vales of reflected electromagnetic waves, amount of moisture in concrete and air temperature should be considered when estimating the content of chloride ions.

(2) From results of estimating the content of chloride ions using electromagnetic wave in the test specimens permeated chloride ions from concrete surface, however it is necessary to carry out experiments varied permeation depth of the chloride ions in the future, it was found that it is possible to estimate the content of chloride ions from the measurement of electromagnetic waves.

(3) From the result of the measurement of the content of chloride ions in reinforce concrete structure, though it was limited condition, it was possible to estimate the content of chloride ions using electromagnetic waves by applying estimated equation of the content of chloride ions obtained from results of tests in the laboratory.

(4) It was made clear that the maximum effective value was largely affected to the estimation of chloride content and amount of moisture content using impedance method in cover concrete.

(5) As he maximum effective value tended to decrease by supplying chloride ions intermittently,

it seemed to find the possibility of estimating migration phenomenon of chloride ions using the impedance method.

(6) In present state, as the change of the maximum effective value is smaller than the change of chloride content and measurements of the maximum effective values greatly fluctuate in the concrete surface, it is necessary to pay attention that chloride content in concrete surface is quantitatively estimated using impedance method.

However, as many problems have been held on application to reinforced concrete structures, further works need to be examined on influences of environmental condition, shape of the structure, moisture condition in concrete, etc..

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