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FUNDAMENTAL STUDY FOR IMPROVEMENT OF ESTIMATION ACCURACY CHLORIDE CONTENT USING ELECTROMAGNETIC WAVES METHOD

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ABSTRACT

Chloride contents estimation using electromagnetic waves as a non-destructive method is effective to conceive degradation of concrete structure, no damage to actual structure and wide range condition would be easily evaluated. From the past study confirmed that the more chloride content is increased in the concrete, the less amplitude value of the electromagnetic waves get. Utilization of this characteristic enables to estimate chloride contents. Giving light on the attenuation characteristics of electromagnetic waves by material change of properties in concrete, and lead the fundamental equation which contributes to estimate chloride contents in concrete using electromagnetic waves. The estimation of chloride contents around reinforcing bars is reported

KEYWORDS : *Electromagnetic Waves, Chloride Contents, Amplitude, Non-destructive Test Method.*

INTRODUCTION

Reinforcement corrosion caused by the presence of chloride ions around the reinforcing bars has been identified as one of the major causes of deterioration of concrete structures. Especially, when cracks caused by reinforcement corrosion were generated in concrete surface, the reinforcement corrosion was accelerated. As the result, cover concrete in the RC member come off and proof stress may be lowered with decrease in the cross section of reinforcing bar. However, a definite understanding about any corrosion of reinforcement is very difficult unless corrosion induced cracks appear on the surface. In order to detect chloride-induced corrosion at an early stage, chloride contents within concrete needs to be investigated using cores drawn from the RC structure, and carrying out chemical analysis. Drawing cores could be structurally unacceptable, damage the reinforcement and only very limited sampling can actually be carried out. In addition, drawing cores to estimate the chloride contents in concrete could not make it possible to investigate the changes in chloride contents over time at exactly the same place.

Thus, development of truly non-destructive tests to estimate the chloride contents in concrete could make it possible to investigate the changes in chloride concentration over time at exactly the same place, without having physically approach the structure, or causing any damage. Such methods would greatly improve our ability to foresee the possibility of reinforcement corrosion at early stages, and enable us to take required corrective action at an appropriate time. From past studies, it was confirmed that the amplitude value of the electromagnetic waves decreases with increasing chloride contents in concrete. It has been reported that electromagnetic waves method is possible to estimate the progress of degradation by attack of chloride ions in concrete structures.

In this study, in order to investigate possibility of application to the estimation method of chloride content using electromagnetic waves in existing structures. In the concrete under the salt damage,

conductivity and permittivity of the medium affect the attenuation of electromagnetic waves. By utilizing the attenuation theory of electromagnetic, the fundamental equation for attenuation simulations of the electromagnetic waves in actual concrete was established. It was confirmed by the electromagnetic wave radar that chloride contents and water contents, and temperature affected the electrical characteristic of concrete. The field survey had been carried out with 5 coastal structures under the different environmental condition, the estimate equation was adjusted in consideration of the above mentioned factors affecting, and it turned out to be more accurate result of calculation. The estimation of chloride contents around reinforcing bars is reported

1. ALGORITHM OF SAE

1.1 Attenuation of electromagnetic waves by chloride contents

The electromagnetic wave which it was emitted from electromagnetic wave radar is reflected by different object of the electrical property, received antenna. It can find placement and the distance of the undergrounding object from the emission of the electromagnetic wave from propagation time required for the reception. The frequency band with this research considers application to cover concrete about 10cm depth, it has 0.5~2.3 GHz (the main is 1.0 GHz) applicable to the frequency band of a radio wave.

Equation 1 shows the electromagnetic waves which advances to the Z-axis direction. In the case of using electromagnetic waves of 1.0 GHz and it is assumed that relative permittivity of the concrete is 8~12 F/m, it can be said that a medium is a low loss. So the attenuation constant α of electromagnetic waves is shown equation 2.

$$E \cong E_0 \exp(-\alpha z) \quad (1)$$

$$\alpha \cong (\sigma/2)\sqrt{\mu/\varepsilon} \quad (2)$$

Where, E: Electric field (V/m), σ : conductivity (mS/cm), μ : permeability (H/m), ε : permittivity (F/m)

Attenuation constant α is varied by the electric characteristic of medium, but permeability in the concrete is constant without any change of electric field.

Although conductivity is not varied by the chloride content, permittivity is varied and greatly affected by the existence of salts which is thought to be caused by the ionic conduction phenomenon of anions (Chloride ions). Both relative permittivity and conductivity is varied by the moisture ratio in the concrete, and greatly affected by the mix proportion and pore size distribution of concrete. Furthermore relative permittivity has dependency on the temperature, the higher temperature the value gets lower.

Table 1 Variation of electrical characteristics with medium

Medium	Conductivity(S/m)	Relative permittivity(F/m)
Fresh water	$10^{-4} \sim 10^{-2}$	80.16±0.05
Sea water	5	81
Dry concrete	$10^{-3} \sim 10^{-2}$	4~12
Wet concrete	$10^{-2} \sim 10^{-1}$	8~20

1.2 Fundamental equation of SAE

Simulation of Attenuation Electromagnetic waves (SAE) is constructed to estimate chloride contents in concrete. The fundamental equation of SAE (equation 3) is based on the Maxwell's electromagnetic equations. The equation is considered electrical characteristics such as permittivity varied by the difference of the condition, mix proportion of concrete, pore size distribution of concrete, temperature and humidity. Magnitudes of electric field (E and E_0 in SAE) are given by the eigenvalue of the electromagnetic wave radar.

$$|E| = \zeta \cdot |E_0| \cdot \exp \left[-\xi_t \xi_w (\sigma + \sigma_{anion}) \cdot \sqrt{\frac{\mu_r \mu_0}{\kappa_t \kappa_w \varepsilon_r \varepsilon_0} \cdot \frac{z}{2}} \right] \quad (3)$$

Where,

$|E|$: magnitude of electric field after transmitted through the concrete (V/m)

$|E_0|$: magnitude of electric field of incident wave to the concrete (V/m)

ζ : composition transmission coefficient

ξ_t : correction factor for the conductivity to be found by temperature of concrete

ξ_w : correction factor for the conductivity to be found by water contents of concrete

σ : conductivity to be found by constitution materials and pore size distribution of concrete (S/m)

σ_{anion} : conductivity to be found by the chloride contents of concrete (S/m)

μ_r : relative permeability of concrete μ_0 : space permeability

κ_t : correction factor for the permittivity to be found by temperature of concrete

κ_w : correction factor for the permittivity to be found by water contents of concrete

ε_r : relative permittivity to be found by constitution materials and pore size distribution of concrete

ε_0 : space permittivity (F/m : $8.85418782 \times 10^{-12}$)

z : propagation distance of a loss medium (m)

[Remarks]

- It is possible to estimate average chloride contents from reinforcing bar to surface of concrete using electromagnetic waves and SAE.
- At any certain depth from surface, chloride contents can be simulated.
- σ and ε_r to be found by condition of mix proportion of test specimens
- Various correction factor ($\xi_t, \xi_w, \kappa_t, \kappa_w$) to be found by the result that analyzed thermal and moisture transfer using weather data such as the outside temperature and precipitation for a certain period before the investigation.

1.1 Attenuation electromagnetic waves by chloride ions

The relationship between the change of the received amplitude value of electromagnetic waves and conductivity with each chloride contents was verified. Electromagnetic wave measurement on chloride ions concentration varied from 0.0 to 1.0%, solution of each concentration filled in the acrylics box. A sheet of steel plate was placed under the acrylics box, and the total reflection amplitude value was compared with conductivity of each sodium chloride solution. The outline and results of the experiments are shown in Fig.1. As the results, it was confirmed that the amplitude value tends to decrease with increasing sodium chloride concentration and electrical conductivity.

Fig. 2 shows results of which made the amplitude value decrement obtained from the experimental result by the x-axis the amount of electric field attenuation obtained from the simulation result (10cm propagation distance) by the y-axis. As the result, since both relations have strong correlativity and it was, the validity of the simulation result was checked. Therefore, it was proved with the increase in the chloride ions in a medium that electromagnetic waves attenuate.

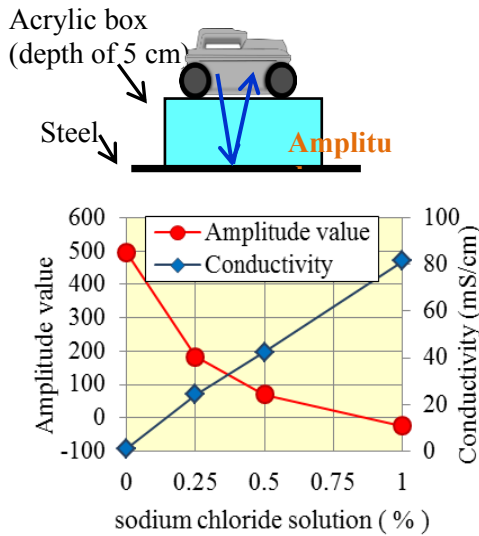


Fig.1 An experiment outline and results

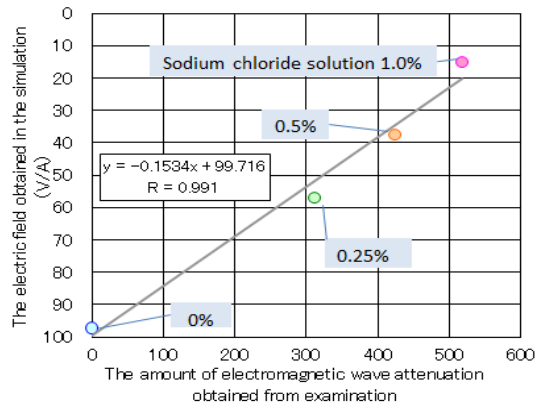


Fig.2 Comparison of an electromagnetic wave attenuation simulation and an actual

1.2 Attenuation electromagnetic waves by water content and temperature

The amplitude of electromagnetic waves was investigated how it would change by the water content and temperature in the medium. In the examination of water content, we measured the urethane sponge which soaked with each solution of 0 and 2.4kg/m³ chloride contents like the above. And in the examination of temperature, we measured the reinforced concrete test specimen (depth of cover is 7cm) in several outside temperatures.

The changes of amplitude value with water contents and temperatures are shown in fig 3. As the result, it was confirmed that the amplitude value tends to decrease with increasing water contents and temperature. From those results, it seems that electromagnetic waves radar can detect electrical characteristics variation by temperature and water contents. In less than 10% of water contents in general concrete, attenuation amplitude value is small. But in case of 10~13% water contents with 2.4kg/m³ of chloride contents medium, it is seemed that there are the point of inflection of the attenuation amplitude. The change is thought to be most likely due to chloride condense in the medium by water evaporation. Further investigation would be expected to resolve those issues.

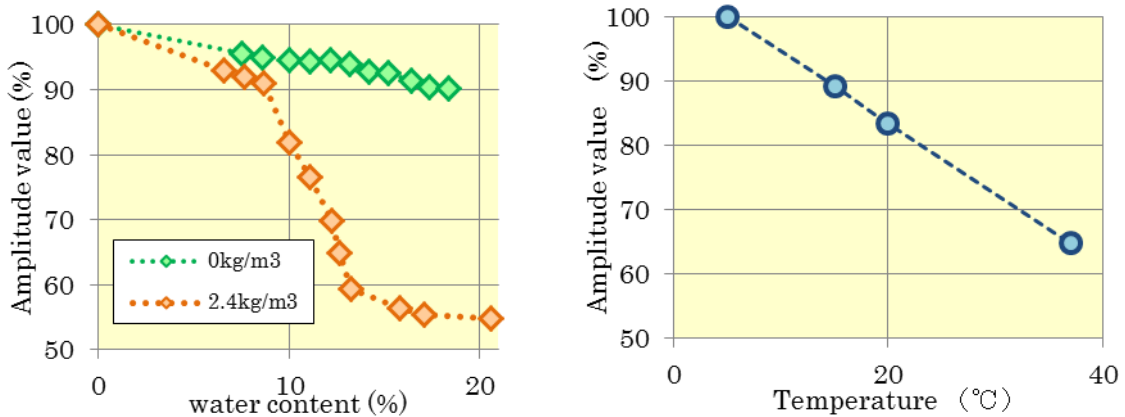


Fig.3 Variation of amplitude value with water contents and temperatures

2. MEASUREMENT OF EXISTING REINFORCED CONCRETE STRUCTURES

For the purpose of investigating the applicability of method of estimating chloride contents using electromagnetic waves in reinforced concrete structures, investigations in several places of coastal structures have been carried out using electromagnetic waves for 4 years. Table 2 shows the investigation year, environmental conditions and condition of mix proportion of concrete in each investigation place.

From past studies, provided that the relationship between amplitude values of electromagnetic wave and various conditions was not linearly independent and it seems that the relationship between amplitude value of electromagnetic wave and various conditions affect mutually. Then, in order to evaluate chloride contents for several structures, the estimation of chloride contents considering the differences of structural member and environmental conditions. For example, The distance with the sea surface as up side of structure (category 1) and side wall at near the sea (category 2) as shown in fig. 4 and 5 are considered. And the form of equation of estimation of chloride contents is shown in following.

$$C_c = \alpha a + \beta c + \gamma t + \sigma \quad (4)$$

Where, C_c is the criterion variable estimated by the multiple regressions analysis, c is depth of cover concrete, t is service life, the amplitude value is a , values from α to σ are coefficient.

As the result, the chloride content intended for several structures can be estimated with good accuracy by considering the differences of structural member and environmental conditions. As the reason, when place into a category, could class the electrical characteristics of the measurement side as the same environmental condition (such as water contents and temperature of concrete) and it followed that estimated precision improved.

Fig. 6 shows the result of comparing the chloride contents obtained by the chemical analysis with the chloride content C_c as the criterion variable estimated by the multiple regressions analysis as the predictor variables using equation of each category.

Table 2 investigation year, environmental conditions and condition of mix proportion of concrete

Investigation year	Field survey No.	Location (Prefecture)	Investigation place	Year of completion	Type of Cement	Water Cement ratio
2010-2013	Field 1	Okinawa	Loading bridge of coal revetment A,B	1974	N	—
				1984		0.54
			Slab and Pier of bridge	1986	FA	0.55
2010-2013	Field 2	Kanagawa	Sea deck	1998	FB	0.45
			Pier of bridge	1966	H	—
2011	Field 3	Okayama	Pier of bridge	1983	BB	0.55
			Duct of utility tunnel	1985		0.58
2011-2013	Field 4	Okinawa	Outlet of hydraulic Power plant	1996	N	0.60
			Underground power plant			
2012,2013	Field 5	Nagasaki	Landing	1978	FA	0.53

N: Ordinary Portland cement

H: High early strength Portland cement

FA: Portland fly ash cement class A

BB: Portland blast furnace slag cement class B

FB: Portland fly ash cement class B



Fig.4 Category 1 Upside of slab Fig.5 Category 2 side wall (near to the sea surface)

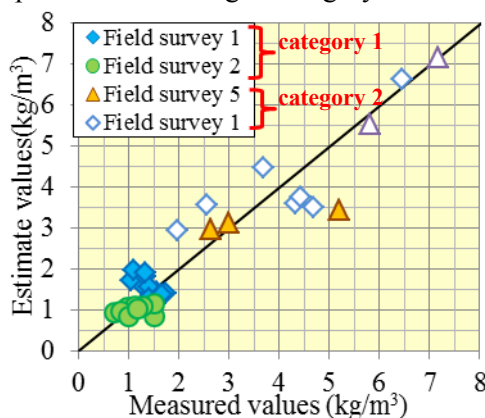


Fig.6 Estimate of chloride contents (category 1 and 2)

3. ESTIMATION OF CHLORIDE CONTENTS AT POSITION OF REINFORCING BAR

The value estimated by SAE is the average chloride contents in the medium. But, it is necessary to perceive chloride contents at the position of reinforcing bar in order to accurately evaluate the progress of the degradation by chloride-induced corrosion. Because of the limit value of corrosion generation of the reinforcing bar by permeation of chloride ion is generally within 1.2kg/m³ to 2.4kg/m³. Fig.7 shows typical distribution of chloride contents and average chloride contents of concrete estimated by SAE. Then, the chloride contents at the position of reinforcing bar is able to estimate at the good accuracy using average chloride contents estimated by SAE, shown in the following. Then total chloride contents permeated from concrete surface to reinforcing bar is calculated by using average of chloride contents in concrete estimated by SAE and depth obtained by using electromagnetic waves measurement. And it is possible to estimate chloride contents at the position of reinforcing bar by applying prediction of the value of diffusion coefficient of chloride ions into concrete with those values using the Fick's law of diffusion. In addition, chloride contents at the concrete surface were able to obtain by potentiometric titrator (JIS A 1154). It is also available for the handy type analyzer using fluorescence X-rays much easier method than the above without any drawing cores.

$$C(x, t) = C_{os} \left\{ 1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_{aps} \cdot t}} \right) \right\} \quad (5)$$

Where, C (x,t) is the chloride contents (kg/m³) of position (length) x (mm) at time t (year)
 Cos : content of chloride at concrete surface (kg/m³), D_{aps} : diffusion coefficient (cm²/year)
 erf : error function

Here, several examples of the results that chloride contents at the position of reinforcing bar in certain coastal structure. Fig.8 shows the bridge in the south of Japan which the one of survey places.

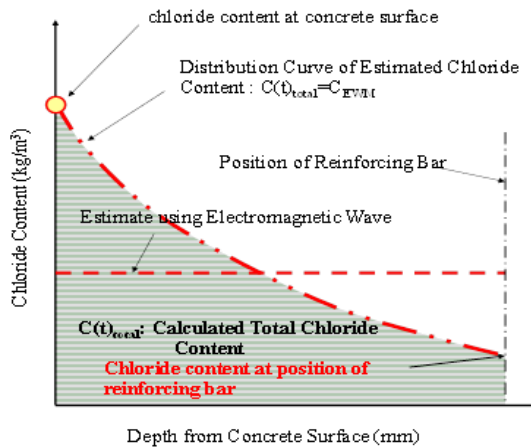


Fig.7 Estimate of chloride contents at position of reinforcing bar Fig.8 Slab and pier of bridge (Okinawa)

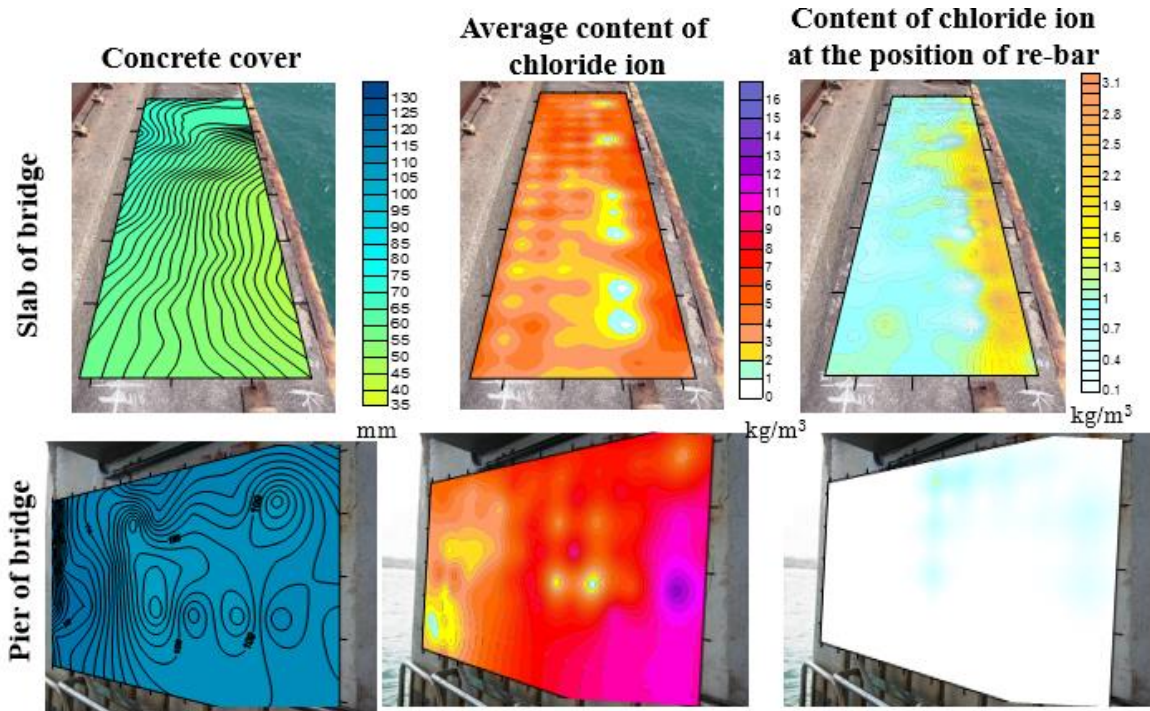


Fig.9 Distribution of concrete cover and estimated chloride contents at slab and pier of bridge

Fig.9 shows the distribution of the results of slab and pier of bridge. The left side shows cover of concrete that obtain by electromagnetic waves. The center shows average chloride contents estimated by SAE. The right side shows chloride contents at the position of reinforcing bar. In comparison with results of slab and pier, average chloride contents of slab were less than that of pier. As the distribution of chloride contents at the position of reinforcing bar of slab, when judged from the limit value of corrosion generation of the reinforcing bar as mentioned above, it seems that it is possible that corrosion of reinforcing bar has been generated in the region shown from the yellow to the red. And the ranges indicate high possibility of corrosion of reinforcing bar of slab much than that of pier, caused by thickness cover of concrete.

Therefore, it is need to found the chloride contents at the position of reinforcing bar and it seems to be possible that the area where countermeasures are necessary is selected. So, it is possible to estimate chloride contents at the position of reinforcing bar by using electromagnetic waves and

SAE, the Fick's law of diffusion. Furthermore it is possible to evaluate the deterioration of widespread concrete structure easily.

4. CONCLUSION

In order to investigate possibility of application to the estimation method of chloride contents using electromagnetic waves in existing structures, fundamental theoretical constructed and the fundamental theory equation established by applying the fundamental equation and attenuation theory of the electromagnetic waves. And in experiments in the laboratory and field surveys, it is confirmed the influence that the electrical characteristic in a medium gave to an electromagnetic waves. The results obtained from this study are shown as follows.

- (1) SAE is composed of conductivity and permittivity in the concrete which is based on the physicochemical phenomenon. Furthermore in order to apply of this method in existing structures, reflection method to fundamental equation which is contracted by the results that analyzed thermal and moisture transfer.
- (2) The amplitude of electromagnetic waves is decreased with increase concentration of sodium chloride solution and electrical conductivity.
- (3) The amplitude of electromagnetic waves is decreased with increase water content and temperature of concrete.
- (4) The chloride contents intended for several structures can be estimated with good accuracy considering the differences of structural member and environmental conditions.
- (5) Possibility of estimating chloride contents at the position of reinforcing bar in existing structures was shown by considering permeation of chloride on the basis of average chloride content obtained from the estimation equation and SAE, and to evaluate the deterioration of widespread concrete structure easily.

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