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Estimation of compressive strength at early age using electric conductivity

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ABSTRACT The techniques using electrical conductivity to estimate compressive Strength of concrete is effective in tunnel construction as concrete structures are greatly affected by demolding time. The study presents a methodology for estimating compressive strength at early age using electric conductivity by carrying out two main tests; compressive strength of different concrete mixes, using ordinary Portland cement (OPC), blast furnace slag type (B) and chemical admixture (A) as an accelerator, water cement ratio 50% (W/C) and monitoring the performance at temperature 5°C–35°C. Electric conductivity test to measure the phenomena of increase in conductivity ratio was conducted. The analysis revealed a model for predicting the compressive strength of concrete mixes at early age (24 hours). From the analysis and the results, there is a relationship between electrical conductivity and liquid water content in the pore in other words, the conductivity ratio and the compressive strength. Therefore using these techniques will provide indispensable techniques for efficient constructions of concrete structures.

1 INTRODUCTION

Many factors influence the rate at which the strength of concrete increases after mixing. Water cement ratio is the most important factor that determined the concrete strength. The effect of water cement ratio of the strength of paste-aggregate bond is similar to its effect on the strength of the paste, i.e. decrease in water cement ratio simultaneously increases the strength of the paste, as well as the strength of paste-aggregate bond. Concrete strength is mainly determined by the strength of the paste and the strength of its bond to the aggregate explaining in turn, why water cement is the most important factor with respect to concrete strength. Hardened time is very important in concrete strength development. The measurement of concrete strength traditionally, is done by preparing concrete cubes or cylinders, then curing them for specified times. Most Conventional curing time is 28 days. The curing temperature is typically 20°C. Hence testing, the cubes or cylinders are crushed in a large press at the different age required.

The strength of concrete is the property most valued by designers and quality control engineers. In essence there exists a fundamental inverse relationship between porosity (volume fraction of voids) and strength. Consequently, in multiphase materials such as concrete, the porosity of each component of the microstructure can become strength-limiting.

Although the water cement ratio is important in determining the porosity of both the matrix and the interfacial transition zone and hence the strength of concrete, factors such as compaction and curing conditions (degree of cement hydration), aggregate size and mineralogy, admixtures type, specimen geometry and moisture condition, type of stress, and rate of loading can also have an important effect on strength. In concrete design and quality control, strength is the property generally stipulated. This is because, compared to most other properties, testing of strength is relatively easy and have significant in constructions of concrete structures. In tunnel construction speed of construction is required without compromising the quality control. Demolding at the time when strength is not stable enough will cause the risk of cracking. Therefore, it is very important to monitoring the strength during the period from placing of concrete to demolding for the quality control of concrete. However, concrete structure is susceptible to environmental factors around, the temperature and humidity

Table 1. Reference value of concrete compressive strength at the time when form and support can be removed.

Type of member surface	Example	Compressive strength of concrete (N/mm^2)
Vertical or near vertical surface of thick member, inclined upper surface small arch outer surface	Footing	3.5
Thin member vertical steeper than 45° or near surface with a slope	Column wall. Side of beam	5
Bridges, slabs and beams of buildings, lower surfaces with a slope lower than 45°	Slab beam the bottom inner	14

as a specimen for quality control. The existing research results focused mainly on the compressive behaviors of compound concrete, and a considerable amount of research done worldwide on concrete strength development has effectively contributed to the development and monitoring of the concrete strength at early age. Unlike the previous study, monitoring technique of hardening process concrete using electric conductivity, this paper investigates the estimation of concrete compressive strength at early age using electric conductivity. This research proposed monitoring method on non-destructive using an electric conductivity meter. That is by estimating compressive strength development in the form. The techniques using electrical conductivity to estimate compressive strength of concrete can be expedient to time reduction during construction. Therefore; this paper harmonizes the two essential factors contributing to the successful completion of project in time and within the budget.

The demolding of concrete must be perform after the concrete has reached the required strength. According to the standard specifications for concrete structures-2012, "materials and construction" Japan Society of Civil Engineers, reference values of demolding strength of each member are listed as shown in Table below.

However, since it is difficult to always confirm the required strength at the actual site, and the timing of demolding. Therefore, developing the techniques to possibly determine the demolding timing by measuring the strength of the concrete in the form in real time, is paramount, it will enhance and perform effective and rational construction.

The authors focused attention on the conductivity (electric conductivity) of concrete as one of methods to estimate the strength of concrete non-destructively and easily. Previous studies on mechanism of compressive strength estimation using electrical conductivity, repair of concrete structure have reported that there is a correlation between the conductivity and compressive strength of concrete. However, the relationship between compressive strength of young aged and conductivity has not been studied.

2 CONDUCTIVITY VARIATION AND INFLUENCE USING ORDINARY PORTLAND CEMENT

2.1 *Measurement accuracy of measured conductivity*

Preliminary, in order to estimate the compressive strength from the measured conductivity, the accurate measurement of the conductivity is examined and these include: investigation of measuring precision of conductivity, then specific dimension of fluctuation factor by measuring the mortars and electric rate and heating rate. The above mentioned measurements are to verified young aged concrete strength and conductivity. In this research, we aimed to estimate the compressive strength of young age of concrete by using conductivity, by defining young age as, an early age when strength is not sufficiently developed yet. For this purpose, the following experiments were conducted. First, identify the factors of fluctuation in conductivity from mortars of various formulations and investigate whether the measured conductivity can capture the change in the hydration reaction caused by the curing accelerator, by preparing concrete using the chemical admixture accelerator. Thereafter, in order to change the compressive strength of young age, concrete of different cement type and ambient temperature was made and the relationship between strength and conductivity of young age was measured.

2.2 *Outline of experiment*

Conductivity is an indicator and the degree to which a specified material conducts electricity, calculated as the ratio of current density in the materials to the electric field that causes the flow of current. It is a reciprocal of resistivity. Conductivity can be mainly used for water quality survey and salinity measurement because electrolyte solution with many has high conductivity. It has been confirmed that the conductivity of cement hydrate changes with elution of ions from cement as time goes by. In order to confirm the measurement accuracy of conductivity, conductivity measurement readings were done.

Blast furnace slag and water replaced with cement so that the change in electric conductivity over time is small. Measurement was made by repeating 32 times immediately after kneading and the variations values were measured.

Figure 1 shows the conductivity meter of the alternative current (AC), two electrode methods used in this study. The electrode were embedded inside the molders, hold tied with thread.

However, since measurement time of about 3 hours is required for measurement of 32 times, measurement with time change is performed at the same time.

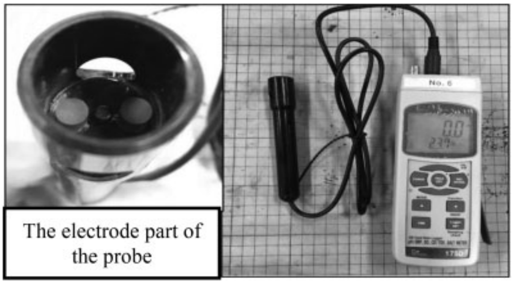

Figure 1. Electric conductivity meter and mould sample.

2.3 *Identification of fluctuation factors of conductivity by measurement of mortar*

As conductivity is an index of electricity flowability and it is thought that it is influenced by the ratio of constituent material such as unit water amount in concrete. Therefore, factors of fluctuation in conductivity depending on compounding conditions were examined. Figure 2 shows the volume composition ratio of mortar. The formulation of the mortar used in a case where the amount of fine aggregate was changed with a certain water cement ratio of 50% and the case where the fine aggregate cement ratio (hereinafter S/C) was 3.0. We examined it in the case of changing unit water quantity. Ordinary Portland cement was used; fine aggregate with a density of 2.62 g/cm^3 was used. For conductivity measurement method, mortar was placed at the tip of the probe and the electric conductivity indicated by the mortar was evaluated 60 minutes after contacting water. The tip of the probe was covered with a vinyl film in order to prevent influence on conductivity due to drying of the mortar.

2.4 *Experimental results and discussion*

From the volume compositions ratio shown in figure 2 it can be seen that the conductivity decreases as the unit fine aggregate quantity increases at the same W/C and increases as the unit water volume increases at the same S/C.

The value shown here is obtained by correcting the variation with time to the conductivity at the start of the measurement. The average value was 0.329 ms/cm, the standard deviation was 0.021, the coefficient of variation was as small as about 6.61%, and it was confirmed that it had relatively high measurement accuracy. From the above results, it is considered that the conductivity measured in this research is highly reliable.

In the above figure 2 the water amount in gram (g) is represented on the axis-y varied and on the other side the Mass ratio on x-axis. The S/C was kept constant. Then, the figure below shows the mass volume significantly responds.

It is believed that the conductivity is evaluated by the conductivity of water containing ions eluted from the cement and the influence of both the resistance of

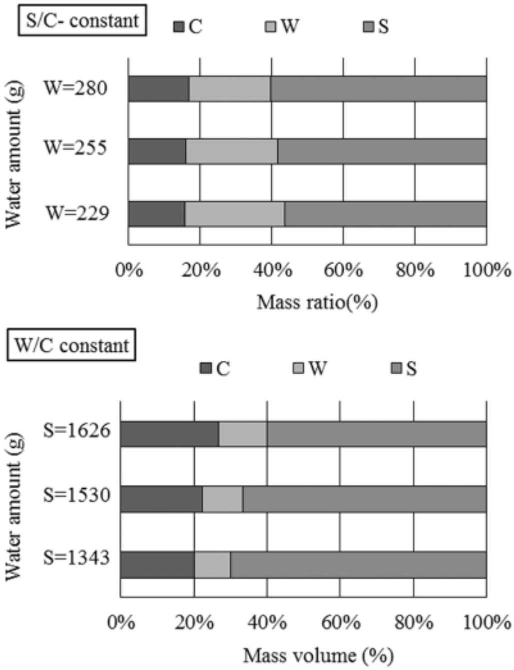

Figure 2. Volume composition ratio of mortar.

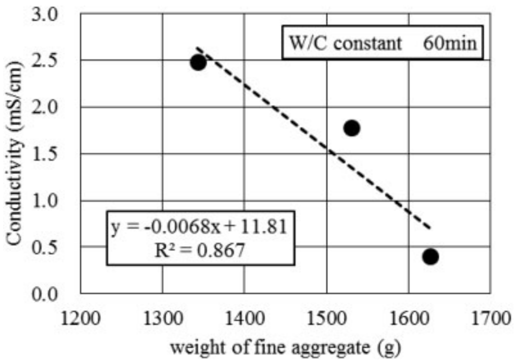

Figure 3. Unit fine aggregate quantity and conductivity.

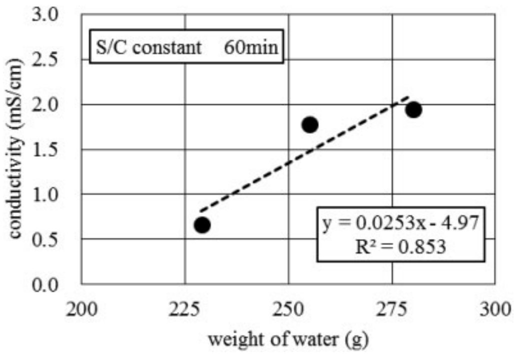

Figure 4. Unit water content and conductivity.

Table 2. Concrete mix proportion for A-series.

Symbol	w/c (%)	s/a (%)	Unit weight (kg/m^3) W	C	S	G	Accelerator add.
A-0%	50	48	175	349	840	938	0
A-4%				349	844	939	4

the fine aggregate. Concrete is a heterogeneous mixture with an interconnected pore network. Depending on the degree of the saturation of the pores (that is, the moisture content), concrete will exhibit conductive characteristics. Also when the fine aggregate quantity increase the conductivity decrease and with increase in water the conductivity increases.

3 MECHANISM OF HYDRATION HEAT AND ELECTRICAL CONDUCTIVITY

3.1 *Materials and test method*

Generally, electricity is passed through the concrete by metal electrodes.

Table 2 above shows the planned concrete mix proportion used in this study. In the A series, in order to change the progress of hydration, a chemical admixture accelerator was added and the addition rate was set to 0% and 4% with respect to the weight of the cement. The aggregate density is 2.62 g/cm^3 for fine aggregate and 2.70 g/cm^3 for coarse aggregate. Figure 5 shows a schematic diagram of the conductivity meter used in this study. As shown in the figure 5, the probe was embedded in the cylindrical specimen. The electrode part was oriented upward so that the electrode part of the probe is not affected by the bleeding phenomenon. Also, to prevent the coarse aggregate from entering the electrode part, the probe was fitted with a wet screened mortar with a 5 mm sieve so as not to affect the measured conductivity. Also, in order to prevent the conductivity from changing due to the influence of drying, the probe was embedded at a position of 50 mm from the surface. Conductivity was measured at 5-minute intervals up to 24 hours of age and then measured at 1 hour intervals until 28 days of age. In order to evaluate the degree of progress of the hydration reaction, hydration heating rate was measured using a conduction calorimeter. The sample was wet screened mortar.

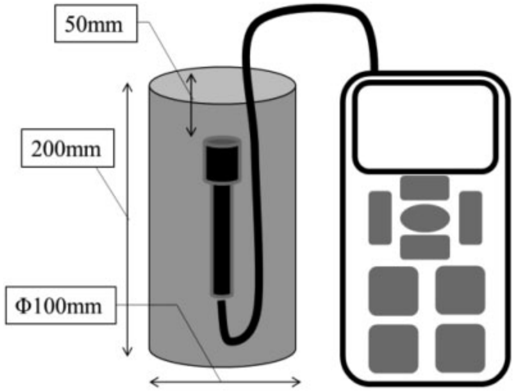

Figure 5. Schematic diagram of the conductivity meter.

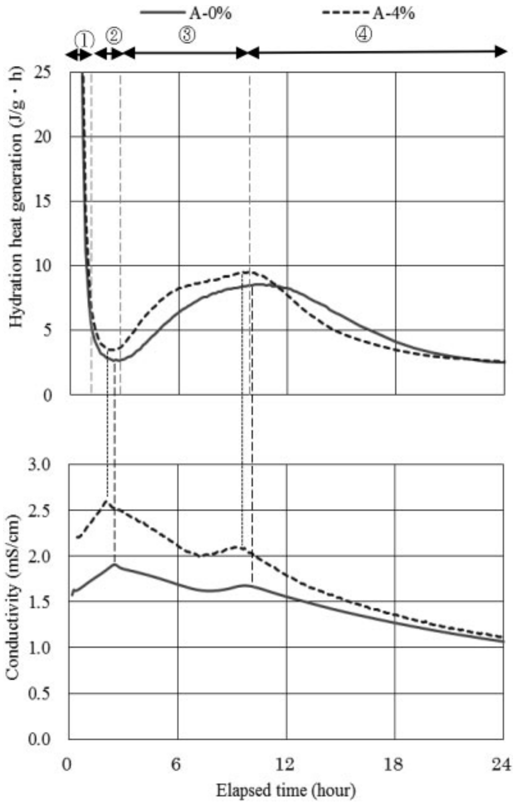

Figure 6. Hydration heat release rate and conductivity.

3.2 *Experimental results and discussion*

Figure 6 shows the measurement results of the conductivity of the A series. The elapsed time was taken as the time from contact water. Conductivity of concrete peaked after about 2 hours and then tendency to decrease. According to the previous study, the tendency of conductivity to increase from water contact is affected by the dissolution reaction of cement. In addition, the tendency of the conductivity to show a peak and then decrease tends to be due to the fact that moisture is consumed as the hydration reaction progresses, making it difficult for electricity to pass through.

From the results up to 18 hours of age, only A-4% is guided by the influence of the chemical admixture accelerator, the electricity increased. However, the conductivities of A-0% and A-4% are not significantly different after the age of 18 hours. Also at A-4%, the peak time of conductivity slightly faster than A-0%.

Next, the relationship between hydration heating rate and conductivity is shown in Fig. Generally, the heating rate is divided into four (4) stages:

In early hydration ((1) in the figure), calcium ions are eluted by dissolution of the cement. In the previous study, it is reported that the concentration of calcium ion increases in about 2 hours from the water contact. The conductivity shows an increasing tendency because electricity tends to flow with ion elution.

In the induction period ((2) in the figure) hydration rate becomes extremely small. In the acceleration phase ((3) in the figure), the reaction becomes active and C-S-H formation and cement hardening occur. Conductivity decreases due to consumption of moisture due to cement reaction. In addition, the movement of ions becomes active, and the conductivity slightly increases. This is thought to be due to the fact that the calorific value of the cement increases at the peak of the heat generation rate.

In the deceleration period ((4) in the figure), the reaction gradually decreases.

The time of the stagnation period of the hydration exothermic of A-4% using the curing accelerator almost coincided with the time of the peak of the conductivity. Also, the time when the hydration exothermic was maximum and the time of the inflection point after the peak of conductivity also roughly agreed. This trend is confirmed with other formulations has been done. From the above results, it can be considered that the change with time of the measured conductivity captures the progress of the hydration reaction.

3.3 *Preparation for conductivity measurement experimental consideration*

Conductivity of the mortar to be measured was confirmed to be measurable with high precision because the coefficient of variation was as low as 6.61%. In addition, conductivity is affected by the unit water amount of compounding conditions, and the conductivity shows an increasing tendency as the unit water amount increases. On the other hand, it was suggested that the fine aggregate could hinder the current flow. Base on this, it turned out that it is necessary to use mortar which performed wet screening in the measurement of concrete. In addition, it is considered that the time-dependent change in the measured conductivity is indicative of the progress of the hydration reaction, and it was confirmed that the change in the hydration reaction due to the addition of the curing accelerator can also be evaluated.

4 RELATIONSHIP BETWEEN STRENGTH AND CONDUCTIVITY OF YOUNG AGE

4.1 *Materials used and specimen specifications*

Concrete mix proportion and curing conditions of concrete set to verify the relationship between compressive strength and conductivity are shown in Table 3.

Table 3. Concrete mix proportion for OPC and B series.

Cement type	w/c (%)	s/a (%)	Unit weight (kg/m^3) W	C	S	G	Curing temp (°C)
OPC 5°C	50	48	175	349	840	938	5
OPC 20°C							20
OPC 35°C							35
BB 5°C	50	48	475	349	837	931	5
BB 20°C							20
BB 35°C							35

Type of cement was ordinary Portland cement (OPC) and blast furnace cement type (B). Also, in order to change the strength development of the concrete, the atmospheric temperature was set at 5°C., 20°C and 35°C. The tests performed here are referred to as OPC and BB series.

4.2 *Test method*

(1) Compressive strength test

The test method was carried out according to Japanese Industrial standard (JIS A 1108) Concrete compressive strength test at the temperature 35°C. The tests performed here are referred to as OPC and BB series.

The test method was carried out in accordance with "Concrete compressive strength Test (JIS A 1108–2006)". The specimen was tested in a state immediately after the prescribed curing was finished. The specimen is placed with an error within 1% of the diameter of the specimen so that its center axis coincides with the center of the pressure plate. The size of the specimen is 100 × 200 mm diameters, in this experiment there were several samples used. The specimens were sealed curing by preserving the form at ambient temperature. The age of the test material was set to 6, 9, 12, 15, 18, 21, 24 hours, and 3,28 days in the OPC series, 6, 12, 15, 18, 24 hours and 3, 28 days in the BB series. In addition, OPC-5°C with slow development of strength was tested at age of 18, 21, 24, 27, 30 hours, and BB-5°C was tested at age of 21 and 24 hours.

(2) Conductivity measurement

Similar to the A series, the conductivity was also measured in the OPC and B series in the same methods.

4.3 *Experimental results and discussion*

Figures 7 and 8 show the compressive strength test results of OPC and BB series. The time when the compression strength became 5.0 N/mm^2 was about 12 hours at OPC-35°C and BB-35°C, 18 hours at OPC-20°C, and 24 hours at BB-20°C. Both OPC and B series showed a difference in strength development due to the difference in ambient temperature.

Next, the results of conductivity of OPC and B series are shown in Figs. 9 and 10. For both OPC and BB series experimental results, the higher the ambient

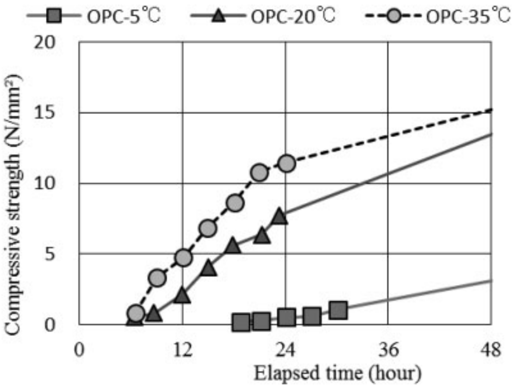

Figure 7. Compressive Strength of OPC Series.

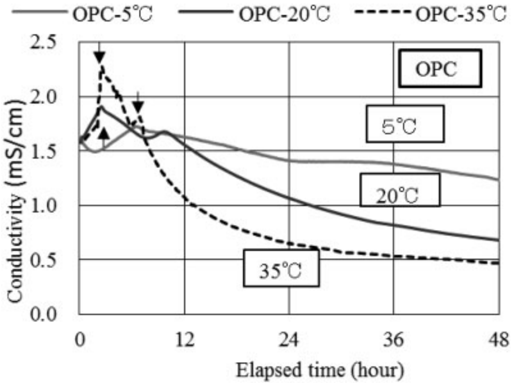

Figure 9. Conductivity of OPC series.

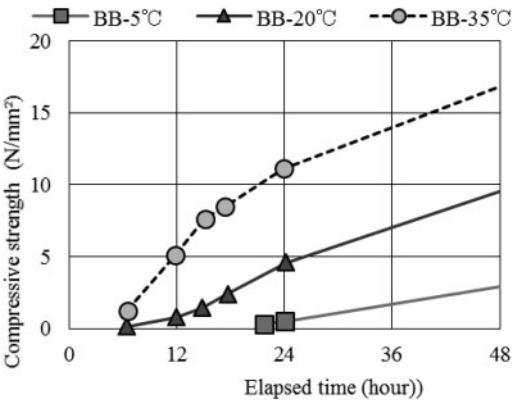

Figure 8. Compressive strength of BB series.

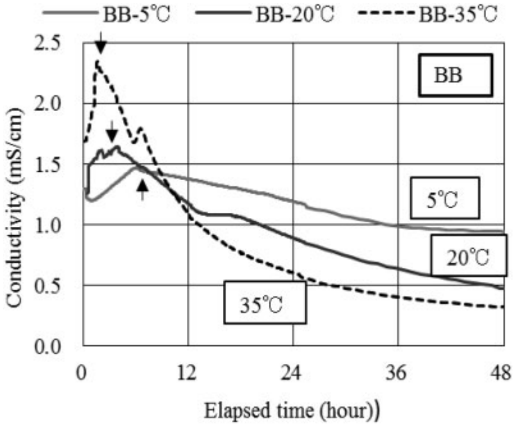

Figure 10. Conductivity of BB series.

temperature, the higher the peak value of the conductivity of concrete, the steep slope after the peak. Also, in the BB series, the peak time of the conductivity became faster as the ambient temperature was higher.

Furthermore, the relationship between the conductivity and compressive strength of OPC and BB series are shown in Figs. 11 and 12. From Fig. 11, the conductivity and compressive strength of the OPC series have the same correlation even at different atmospheric temperatures of 5° 20° and 35°. From Fig. 12, it was confirmed that the conductivity and compressive strength have the same correlation at B-5° and BB-20° like the OPC series, but at BB-35°, the difference with other temperature conditions is realized. In the case of using blast furnace cement B type, conductivity and compressive strength show different correlations under high temperature condition of 35°.

Therefore, further investigation is necessary to check and clarify more about the phenomena.

The authors believed that, the consumption of moisture due to the hardening of concrete, that is, the progression of hydration is related to the decrease in conductivity and the increase in compressive strength.

5 ESTABLISHMENT OF ESTIMATION METHOD FOR STRENGTH OF YOUNG AGE

In order to estimate concrete strength at early ages based on the results of previous tests, a curve was estimated to estimate compressive strength from conductivity within 3 days of age in OPC series. The estimation equation is shown in equation (1).

$$Y = -13.44 \ln(x) + 6.93 \tag{1}$$

Where, y: compressive strength (N/mm^2)
x: conductivity (mS/cm)

Here, in order to investigate whether it can be operated even in different temperature environments, the strength estimation was verified using the concrete having the same formulation as the OPC concrete in Table 3. The atmospheric temperature of the concrete used for verification was 28°C. The time required to develop compressive strengths of 3.5 N/mm 2, 5.0 N/mm^2, and 14.0 N/mm^2, which are the strengths required by the specifications as shown in Table 1, were

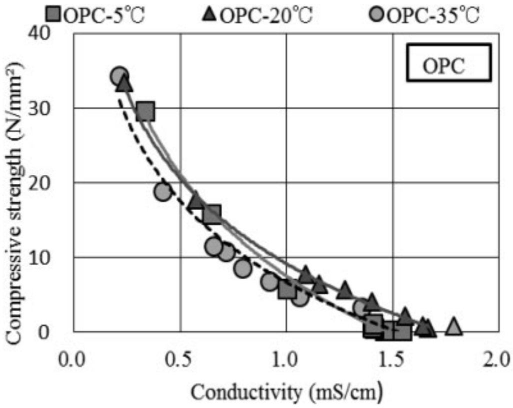

Figure 11. Conductivity and compressive strength of OPC series.

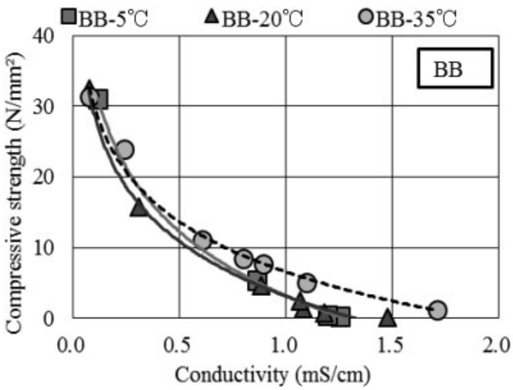

Figure 12. Conductivity and compressive strength of BB series.

estimated from the formula (1) Time, 14.0 hours and 40.0 hours, so the compressive strength test was carried out at that time. Figure 13 shows the test results. All compressive strengths performed in the confirmation experiments showed higher values than the estimated intensities.

From these results, conductivity evaluated the degree of progress of hydration reaction and confirmed that it correlates with moisture in concrete reported in the previous study. From these facts, we think that there is a possibility that consumption of moisture due to hardening of concrete, that is, an increase in compressive strength due to the progress of hydration can be predicted by the degree of decrease in conductivity.

Correlation to the conductivity ratio and compressive strength was observed, but the relationship is different in each mix proportions. In the future, further improvement for accuracy of estimation of intensity is considered necessary and to examine factors that affects the measured conductivity and to improve the accuracy of compressive strength estimation formula.

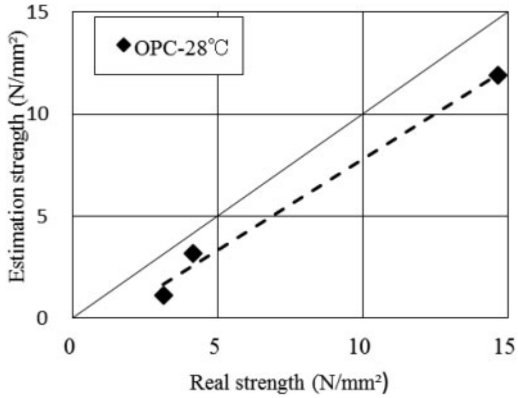

Figure 13. Actual strength and estimated strength at OPC-28°C.

6 CONCLUSIONS

Based on the results of current investigations, the following conclusions are drawn:

(1) The electrical resistivity of concrete is significantly affected by the porous network and interconnection, conductance of pore fluid, temperature and degree of saturation hence concrete strength.
(2) Investigation of variations in electrical conductivity of concrete using blast furnace slag and plaster showed that the variation coefficient is as small as 6.61%, and highly reliable evaluation is possible.
(3) The higher the ambient temperature, the larger the peak value of the conductivity of concrete and the steep slope after the peak.
(4) The relation between the conductivity and compressive strength of concrete in OPC concrete has almost the same correlation irrespective of ambient temperature, and compressive strength can be estimated from conductivity even if the ambient temperature changes.
(5) There is a possibility that the relationship between conductivity and compressive strength at an ambient temperature of 35°C tends to be different from other ambient temperatures in the BB concrete.
(6) When compressive strength was estimated from conductivity for OPC concrete, it was confirmed that the estimated strength is slightly lower than the actual strength.
(7) The timing at which the peak of conductivity peaks is almost equal to the induction period of the heat generation rate that can be confirmed by the conductivity calorimeter, and the timing at which the conductivity changes is almost equal to the timing at the end of the acceleration period of the heat reaction, and concrete which is re-ported in the previous researches.
(8) Electrical conductivity method proves to be an effective and reliable method for assessing various characteristics of concrete especially concrete strength development at early age. Moreover

being a non-destructive test, so, it is possible to estimate the compressive strength with electrical conductivity.

When placing concrete, we can estimate the concrete strength at arbitrary position by embedding the probe in the actual concrete structure such as tunnels and any other concrete structures.

(9) In this method, the conductivity of mortar in the tip of the probe is measured. Therefore, the range in which conductivity is being evaluated is small. Unless reinforcing bar is placed at the tip of the probe, the measured conductivity has little effect on the reinforcing bars.

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