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Effect of Electrical Resistivity of Mortar Surface Layer on Drilling Speed Using Mix Proportion

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Abstract

In this study, we conducted electrical resistivity tests and small-diameter drilling tests on mortar surface layers using water-cement ratio and unit water content as experimental factors, and we investigated the effect of electrical resistivity on the drilling speed. Results showed that water content had a considerable effect on electrical resistivity depending on the water-cement ratio. Further, an increase in water-cement ratios tended to increase the drilling speed, which indicated a highly positive correlation. Moreover, the quality of the mortar surface layer could be estimated by the drilling speed even when the difference in the water-cement ratios was

approximately 5%. However, the effect of the unit water content was small and did not have any specific relationship with electric resistivity, water content, or drilling speed.

Keywords: *mix proportion, mortar, electric resistivity, water content, small-diameter drilling test, drilling speed*

1. Introduction

The concrete surface layer corresponding to the reinforcing bar cover also controls the structural durability; thus, it is extremely important to accurately diagnose its quality for structural maintenance [1]. In this regard, destructive tests for quality assessment with core sampling have high estimation accuracies but cause large amounts of damage to buildings, thereby limiting their applications. On the contrary, existing non-destructive tests are considered to have some degree of reduced reliability since they indirectly estimate the material quality, and there are different problems for each diagnostic method. Therefore, development of a diagnostic method that uses minimally destructive tests is highly crucial, which causes little damage to buildings and facilitates the evaluation of material quality of concrete structures with a high degree of accuracy.

The small-diameter drilling tester used in this study is similar to the minimally destructive testing device developed by Hasegawa et al. [2]. The damage caused by this device on the measured object is extremely small using a drilling diameter of approximately 3 mm. This device may be able to estimate the concrete compressive strength or material quality of the surface layer using a suitable drilling speed [3]. Yasue et al. [4] also reported that the drilling speed and air permeability (mass transfer resistance) were correlated, thereby suggesting the possibility of evaluating the material quality of hardened mortar surface layers using a drilling speed. However, limited research has been conducted on methods to evaluate the material quality of surface concrete layers using drilling speeds. Comparisons with material quality estimation indices other than air permeability are also mandatory to establish methods for evaluating the material quality of surface concrete layers with higher accuracies using drilling speeds.

Therefore, in this study, we considered the electrical resistivity using the four-electrode method established by the Japan Society of Civil Engineers [5] as a material quality estimation index instead of the air permeability. The electrical resistivity is considered a factor to evaluate the mass transfer resistance and water content of cover concrete, and clarifying its relationship with the drilling speed would be meaningful in achieving the objective of material quality evaluation. Therefore, we examined the effect of the electrical resistivity of the hardened mortar surface layer on the drilling speed using the water-cement ratio and unit water content as experimental factors. We used mortar as the effects due to the materials used and material constituents appear clearly in the sample.

2. Effect of water-cement ratio on electrical resistivity and drilling speed (Experiment 1)

2.1. Experimental factors

The water-cement ratio was used as the experimental factor with four values of 35, 45, 55, and 65 %.

2.2. Mortar materials used and mix proportion

Tables 1 and 2 show the mortar materials used and mortar mix proportions, respectively. Same unit fine aggregate amounts were used to clarify the effect of the water-cement ratio. The air content (8±2%) and flow value (190±20) were also adjusted with the unit admixture amount within a certain range.

Table 1. Mortar materials used (Experiment 1 and 2)

Materials	Type	Notes	Symbol
Cement	Ordinary Portland cement	Density:3.16 g/cm^3 Specific surface area:3480 cm^2/g	C
Fine aggregate	Dried silica sand (No.4, No. 5)	Absolute dried density:2.54 g/cm^3 Mixing ratio 1:1	S
Chemical admixture	High-performance AE water reducing agent	Main component: Polycarboxylic acid copolymer	AD
Water	Tap water	—	W

Table 2. Mix proportion of mortar (Experiment 1)

No.	W/C	Air (%)		Flow value		S/C	Unit weight (kg/m^3)			
	(%)	Target	Measured	Target	Measured	(wt)	C	W	S	AD
1	50	8±2	9.0	190±20	182	2.53	508	254	1284	0.72

2	55		7.6		190	2.68	479	263		0.52
3	60		7.6		202	2.84	452	271		0.55
4	65		7.2		203	3.00	428	278		0.23

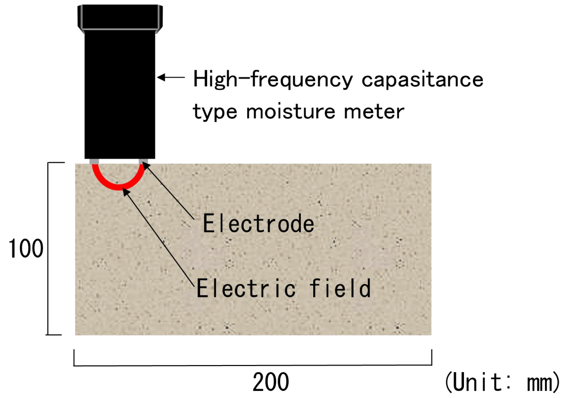

Figure 1. Measurement principle of water content test

2.3. Experimental method

2.3.1. Mortar mixing and flow tests

The mortar mixing and flow tests were conducted according to JIS R 5201, "Physical Testing Methods for Cement (10.4.3. Mixing Methods and 11. Flow Test)".

2.3.2. Air content tests on fresh mortar

For the air content of the mortar, the unit mass was measured according to JIS A 5002, "Lightweight Aggregates for Structural Concrete (5.12.d. Measurement of Unit Mass of Mortar)" and calculated according to JIS A 1116, "Method of Test for Unit Mass and Air Content of Fresh Concrete by Mass Method(6.2. Air Content)."

2.3.3. Sample and curing methods

A prism with the base of 100×100 mm and the height of 200 mm was used as the sample, which was packed in two layers in a steel mold, where the upper layer was formed by leveling it with a trowel.

The sample was cured in standard water for a material age of 28 days, after which it was cured in air for a material age of 91 days, which was set as the test day.

2.3.4. Moisture content tests

Figure 1 shows the moisture meter based on the high-frequency capacitance method used for the moisture content test. As shown in Figure 2 , the moisture content was taken as the average of the measured values, and two measurements each from the upper and lower sections were taken for one side surface of the prismatic sample. There were two test samples per standard; however, the water content values given in Section 2.4 do not represent the average values of the two samples but those obtained for each sample.

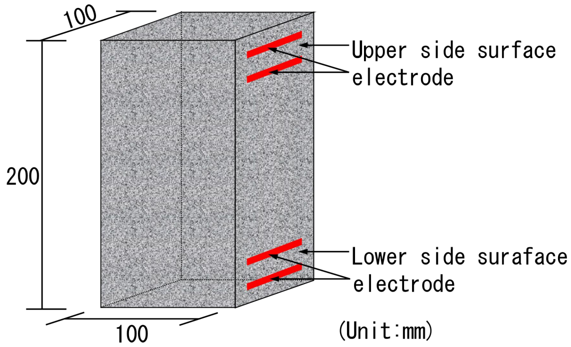

Figure 2. Measurement positions of water content test

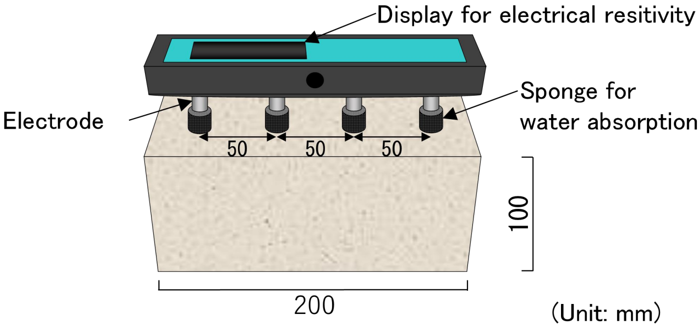

Figure 3. Electrical resistivity measurement device

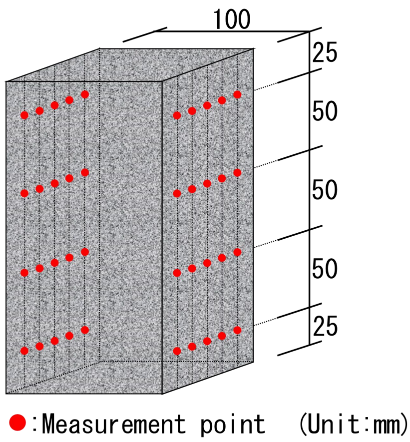

Figure 4. Measurement positions of electrical resistivity

2.3.5. Electrical resistivity tests

Figure 3 shows the electrical resistivity measurement device based on the four-electrode method, which was used for the electrical resistivity test. The electrical resistivity measurement positions are shown in Figure 4. To measure the electrical resistivity, four electrodes moistened with water were pressed against the sample, two electrodes on the outer side applied an alternating current to flow through the sample, the potential difference between the two electrodes on the inner side was measured, and finally, the electrical resistivity was calculated using the evaluation equation (1) based on the Wenner method (see Figure 5). As shown in Figure 4, the average of ten measured values (ten rows) of electrical resistivity was used for the two side faces of the prism and five times (five rows) for each face. Similar to that of the water content, the electrical resistivity values shown in Section 2.4 are not the average of the two samples but for each sample.

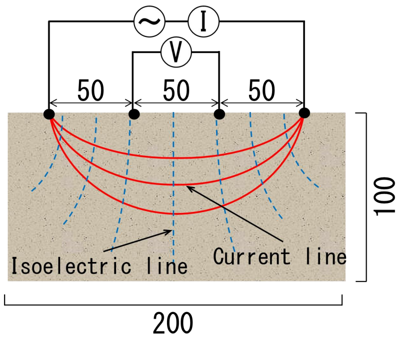

Figure 5. Measurement principles electrical resistivity according to Wenner method [5]

$$\rho = \frac{2\pi a V}{I} \qquad (1)$$

Notes; ρ: electrical resistivity (kΩcm), a: distance between electrodes (5 cm),V: potential difference between electrodes (V), I: current flowing through the specimen (A)

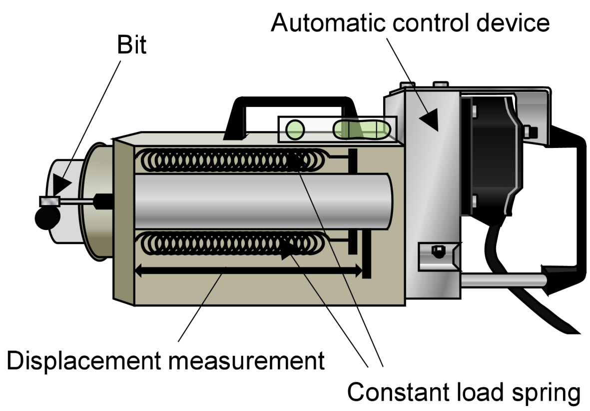

Figure 6. Small-diameter drilling tester

2.3.6. Small-diameter drilling test

The small-diameter drilling tester shown in Figure 6 was used for the small-diameter drilling test. This tester uses two load springs of spring constant 14 N, presses a φ2.8 mm diamond bit against the measurement location, and drills holes to a depth of approximately 10 mm using a motor controlled with a constant torque and rotation speed.

The measurement positions of the drilling test are shown in Figure 7. The small-diameter drilling test was conducted with the same samples used in the electrical resistivity test. Two samples for each standard were used similar to the electrical resistivity test. Furthermore, drilling was conducted at six points, each at heights of 50 mm and 150 mm on one side face of the sample. The average drilling speed for a total of 12 measurements was used for the sample. Therefore, the drilling speed given in Sections 2.4 and 3.4 represents the value obtained for each sample similar to that of the electrical resistivity test. Although discussed later, a reference mortar, created with only fine aggregates less than 0.6 mm diameter, was drilled before and after the drilling test of the samples for each standard to achieve an optimal drilling speed. The flowchart of the drilling speed calculation and correction is shown in Figure 8, while the symbols shown in this study and their definitions are summarized in Table 3. The drilling speed calculation and correction processes are further described in detail below.

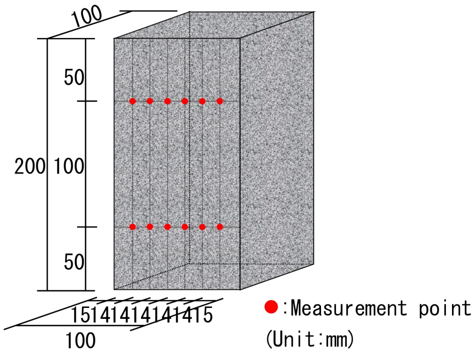

Figure 7. Measurement positions of small-diameter drilling test

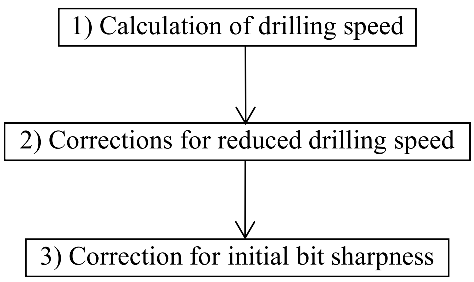

Figure 8. Flow of calculation and correction of drilling speed

Table 3. Symbols and definitions used in this article

Symbol	Definitions
V_p	The drilling speed, V_p, is the average of the intervals where the drilling speed is in the range of 0.13–0.40 mm/s and the drilling speed continues in the range of 0.20–0.40 mm in distance. This is a value that is assumed to mainly correspond to the drilled cement paste. It also includes the results of drilling fine particles with a diameter less than the bit diameter in the fine aggregate. However, if the drilling speed, which is presumed to be the boundary between the different materials, changes more than 0.20 mm/s within the aforementioned range, it is excluded.
V_m	The drilling speed, V_m, is the slope obtained by linearly approximating the relationship between the drilling depth and drilling time (graph). Unlike the drilling speed, V_p, from which only the cement paste is extracted shows the average drilling speed for the entire concrete. However, the section where only the aggregate or the void is drilled, is excluded from the approximate range.
rV_f	The drilling speed, V_m, for the reference mortar (0–5 mm depth), at the start of drilling is shown.
rV_e	The drilling speed, V_m, for the reference mortar (0–5 mm depth), at the end of drilling is shown.

1) Calculation of drilling speed

An example of the relationship between the drilling speed and drilling depth is shown in Figure 9. The measurement interval of the drilling depth was set at 1/100 s for this experiment, and the 11-point moving average method was used to measure the drilling depth, after which the moving average value was extracted every 1/25 s to calculate the drilling speed. Extremely small drilling speeds were seen in sections containing aggregates but became extremely high in void or material boundary sections. Therefore, sections where the cement paste was considered to be drilled (represented by red lines in the figure) were extracted for this study. The drilling speed in each drill test was calculated by averaging these values. The drilling speed, Vp, at each measured face was taken as the average of 12 drilling speeds obtained from the two samples. Please refer to reference [2] for the extraction criteria of Vp. As the material quality evaluation of the top-most layer was main the objective of this study, the value calculated in the 0–5 mm drilling depth range was used as the drilling speed Vp.

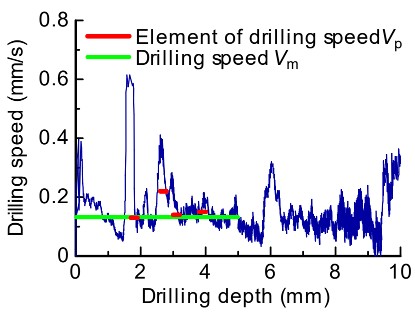

Figure 9. Example of relationship between drilling speed and drilling depth (W/C=50 %, lower side of surface)

2) Correction for reduced drilling speed

The bit sharpness decreases roughly linearly with the increase in the number of drilling operations as the diamond particles on the bit tip wear out [2]. However, these particles are heavily worn out in actual practice when drilling high-strength, hard materials for long periods of time; thus, it is difficult to evaluate the extent of decrease in sharpness with just the number of drilling conducted. Therefore, this study tests were conducted with a single bit for each standard, and the drilling speed at the side face obtained by procedure 1) was corrected by assuming that the bit sharpness linearly decreased with increase in the cumulative sum obtained by multiplying the drilling depth and drilling time for each drilling operation. For a given face, the bit sharpness at the start of drilling tests was assumed to decrease by the cumulative sum of the drilling depth and drilling time of the drilling up to the end of the drilling test for the face immediately before this test; therefore, the drilling speed was corrected for each measured surface.

3) Correction for initial bit sharpness

The bit sharpness also varies due to the mounting direction (angle) in addition to variations within the bit itself [2]. Therefore, the drilling speed obtained by procedure 2) was corrected using the drilling speed rVf of the reference mortar drilled before the drilling test for each standard to compare the drilling speed for each standard. rVf was based on a water-cement ratio of 50 % mentioned in Section 2 and a unit water content of 259 kg/m3 mentioned in Section 3.

In this study, we discuss subsequent experimental results with the drilling speed calculated and corrected as the drilling speed Vp using the above-mentioned procedures 1) – 3).

2.4. Experimental result and discussion

2.4.1. Effect of water-cement ratio on electrical resistivity

Figure 10 shows the relationship between the electrical resistivity and water-cement ratio. An increase in the water-cement ratio also tends to increase the electrical resistivity, and that the two are correlated. The water-cement ratio and electrical resistivity were generally believed to have a negative correlation, but our experimental results exhibited the opposite trend. Therefore, we measured the water content of each sample. Figure 11 shows the relationship between the electrical resistivity and water content. When the water-cement ratio was 55 %, the measured water content was extremely small for one sample, which was excluded from the test values. The figure also shows that an increase in the water-cement ratio decreases the water content and increases the electrical resistivity. According to this study [6], the surface layer of samples cured in air was reported to dry more easily with a higher water-cement ratio, and it was found that the effects of water content on electrical resistivity would increase as such. Therefore, the water content had a higher impact than the water-cement ratio on the electrical resistivity, and it was considered that this resulted in its positive correlation with the water-cement ratio. Therefore, the effects due to water content must be sufficiently considered, and the relationship between electrical resistivity and mass transfer resistivity must be investigated after appropriate corrections for measured objects with varying water content (unsaturated conditions).

2.4.2. Effects of water-cement ratio on drilling speed

Figure 12 shows the relationship between the drilling speed Vp and water-cement ratio. An increase in the water-cement ratio tends to increase the drilling speed Vp, and a strong correlative relationship between them is seen. Therefore, Vp could be used to estimate the material quality of the hardened mortar surface layer even with water-cement ratio differences of approximately 5 %.

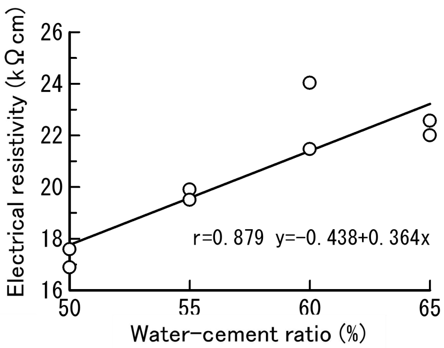

Figure 10. Relationship between Electrical resistivity and water-cement ratio

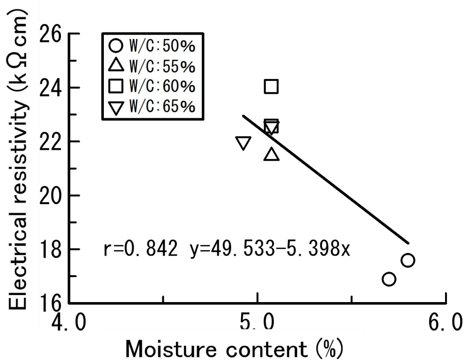

Figure 11. Relationship between Electrical resistivity and water content

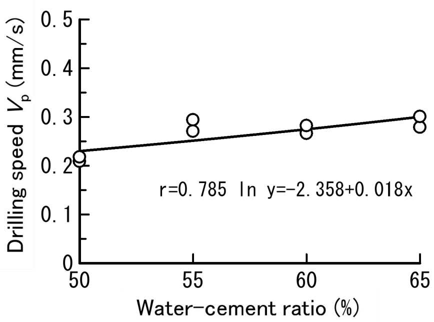

Figure 12. Relationship between Drilling speed and water-cement ratio

2.4.3. Relationship between electrical resistivity and drilling speed

Figure 13 shows the relationship between the drilling speed Vp and electrical resistivity. An increased electrical resistivity resulted in a gradual increase in the drilling speed Vp, which indicate a positive correlation, too. As previously mentioned, this was can be attributed to the effect of the relationship between the water-cement ratio and electrical resistivity caused by the water content.

3. Effect of unit water content and on electrical resistivity and drilling speed (Experiment 2)

3.1. Experimental factors

The unit water content was set as the experimental factor, and four values of 259, 266, 273, and 280 kg/m3 were used.

3.2. Mortar materials used and mix proportion

The mortar material used was the same as that mentioned in Section 2.2, and Table 4 shows the mortar mix proportion based on the unit water volume. The water-cement ratio was kept constant to clarify the effect of unit water volume. The air content (8±2%) and flow value (190±20) were also adjusted with the unit admixture amount within a certain range.

3.3. Experimental methods

Same experimental methods as that mentioned in Section 2.4 were used.

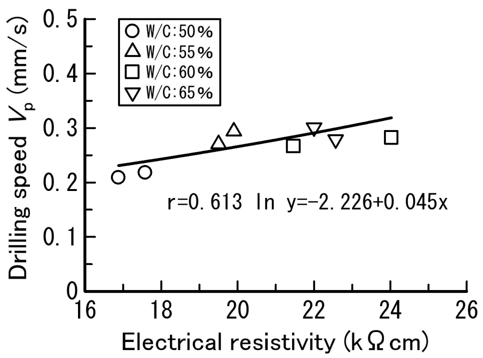

Figure 13. Relationship between Drilling speed and electrical resistivity

Table 4. Mix proportion of mortar (Experiment 2)

No.	W/C	Air (%)		FL		S/C	Unit weight (kg/m³)			
	(%)	Target	Measured	Target	Measured	(wt)	C	W	S	AD
1	55	8±2	7.6	190±20	195	2.76	471	259	1300	0.91
2			7.5		199	2.63	484	266	1273	0.51
3			6.6		195	2.50	497	273	1243	0.22
4			6.4		198	2.39	509	280	1217	0.00

3.4. Experimental result and discussion

3.4.1. Effect of unit water content on electrical resistivity

Figure 14 shows the relationship between the electrical resistivity and unit water content. No specific relationship between the unit water content and electrical resistivity exists.

Figure 15 shows the relationship between electrical resistivity and water content. A smaller water content tended to increase the electrical resistivity, and a similar trend as that in Figure 11 is observed. However, the relationship with electrical resistivity is not uniform when considering the unit water content. As stated in Subsection 2.4.1, this was believed to be attributed to the fact that water content has a major effect on the electrical resistivity, and a same water-cement ratio has a dominant effect. Therefore, it is presumed that the effect of the unit water content could not be sufficiently determined within the scope of this experiment.

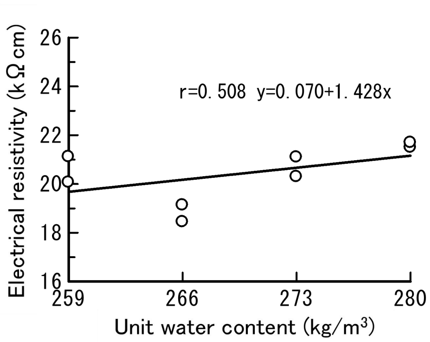

Figure 14. Relationship between Electrical resistivity and unit water content

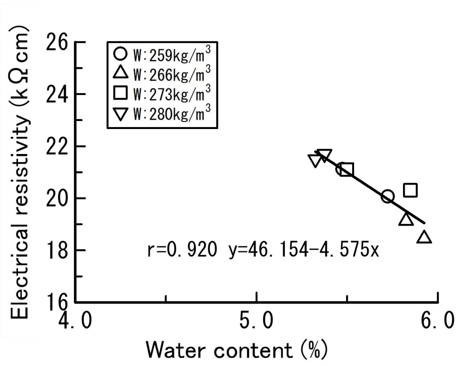

Figure 15. Relationship between Electrical resistivity and water content

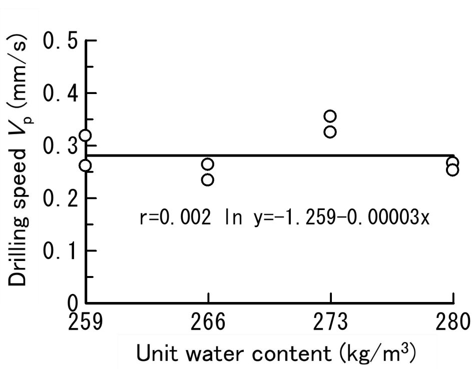

Figure 16. Relationship between Drilling speed and unit water content

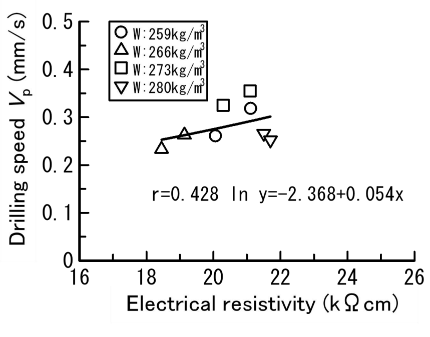

Figure 17. Relationship between Drilling speed and electrical resistivity

3.4.2. Effect of unit water content on drilling speed

Figure 16 shows the relationship between the drilling speed Vp and unit water content. Evidently, no specific relationship between them exists. As previously mentioned, this was believed to be due to the dominating influence of the water-cement ratio, which determines the strength and the structure of the hardened body.

3.4.3. Relationship between drilling speed and electrical resistivity

Figure 17 shows the relationship between drilling speed Vp and electrical resistivity. An increase in the electrical resistivity tends to result in gradually increasing drilling speed Vp, and a positive correlation similar to that in Figure 13 is observed. As mentioned in Subsection 3.4.1, this was believed to be largely affected by the water content caused by the electrical resistivity.

4. Conclusions

The following conclusions can be drawn from the experimental results.

1. The water content of the sample surface layer had a major effect on the electrical resistivity, and an increased water-cement ratio also tended to increase this.
2. The drilling speed Vp exhibited a strong correlation with the water-cement ratio but no specific relationship with the unit water content.
3. Within the scope of this experiment, it was considered that the drilling speed Vp is useful to evaluate the material quality on the mold surface even with water-cement ratio differences of approximately 5%.
4. All experimental factors within the scope of this experiment were greatly affected by the water content, and drilling speed Vp also tended to increase with increased electrical resistivity.

In the future, we want to investigate in detail the effect of water content on electrical resistivity and propose a simple correction method for the electrical resistivity based on water content.

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