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Research article

Influence of concrete bleeding due to mix proportion on the drilling speed of hardened surface layer

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Abstract: The significance of micro-destructive testing, which can estimate the durability of reinforced concrete structures with minimal damage and high accuracy, in the investigation and diagnosis of reinforced concrete structures has been increasing. This study aims to evaluate the quality of the surface layer of concrete structures via a small-diameter drilling test, which is one of the micro-destructive tests developed to estimate the strength of concrete. Hence, it would be possible to evaluate the quality and strength of concrete simultaneously, which is very important.

In this study, the influence of the bleeding amount which affects the surface quality of concrete on the drilling speed, was experimentally studied, considering the water-cement ratio and unit water content as experimental factors. The influence of bleeding on the drilling speed of the specimen surface was also investigated through measurements at the top and bottom surfaces.

The following points were clarified from the experimental results and their analysis. (1) The drilling speed changes depending on the water-cement ratio and the unit water content. (2) The amount of bleeding affects the drilling speed; however the drilling speed is affected by the volume of the fine aggregate in the specimen. Therefore, (3) there is a possibility that it can be used for surface quality evaluation of concrete by examining in detail the method for calculating and correcting the drilling speed.

Keywords: mix proportion; bleeding; surface quality; small-diameter drilling test; drilling speed

1. Introduction

Bleeding is a phenomenon wherein a portion of the mixing water is released and it rises to the upper surface as the aggregate and cement particles settle; bleeding induces vulnerability to the upper layers of concrete, thereby decreasing its durability and strength [1]. Therefore, it is important to understand the behavior of bleeding to evaluate the quality of the upper layer of concrete. For example, if the bleeding amount increases, the mass transfer resistance of the upper layer decreases; this affects the distribution of air permeability along the height direction [2].

Furthermore, in the field of durability evaluation of concrete structures, there are high expectations for semi-destructive testing, which can evaluate the durability of concrete structures, with a higher accuracy than the existing non-destructive tests and causes lesser damage than core sampling. The small-diameter drilling tester [3,4], which has been studied by the authors, falls under the category of the semi-destructive tester, and it drills approximately 10 mm from the surface of the object to be measured with a diamond bit of 2.8-mm diameter. In previous studies, the relationship between the drilling speed attained by this tester and the compressive strength of concrete [3] and the air permeability of a mortar surface [5] have been investigated. As a result, the quality of the surface may potentially be assessed based on the drilling speed.

However, the relationship between drilling speed and bleeding remains to be elucidated. Further, it is advantageous to be able to determine the effect of bleeding on the distribution of quality at the column and wall side elevations and on the quality of the upper layers, including the floor slab, at various drilling speeds. If this can be achieved, the applicable range of the small-diameter drilling tester can be further expanded, and the evaluation of quality and durability of the various physical properties of the surface layer of concrete can be realized.

In this study, the influence of the bleeding of concrete due to the mix proportion on the drilling speed of the hardened surface layer is examined. Moreover, the influence of bleeding on the drilling speed of the specimen surface layers is examined from the test results of the top and bottom surfaces of the specimens. As a result of the investigation, no particular trend was observed in the drilling speed of the upper and lower surfaces of the specimens, although a trend between the water–cement ratio and the drilling speed has been observed in a previous study [5]. The originality of this study lies in the fact that the relationship between drilling speed and bleeding is investigated, which had not been studied before.

2. Influence of water-cement ratio on bleeding amount and drilling speed (Experiment 1)

2.1. Experimental factor

The water-cement ratio was considered as the experimental factor. The ratio was set at the following four levels: 50%, 55%, 60%, and 65%.

2.2. Materials and mix proportion of concrete

Table 1 presents the materials used, and the mix proportions of concrete are tabulated in Table 2. The air content (4.5 ± 1.5%) and slump (18 ± 2.5 cm) were adjusted to ensure that the amount of unit chemical admixture stays within a certain range.

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

Material names	Types	Remarks	Symbol
Cement	Ordinary Portland cement	Density: 3.16 g/cm^3	C
Fine aggregate	Land sand from the Oigawa River system	Absolute dry density: 2.58 g/cm^3	S
Coarse aggregate	Crushed stone from Okazaki	Absolute dry density: 2.66 g/cm^3	G
Chemical admixture	AE water reducing agent	Complexes of modified lignin sulfonic acid compounds and polycarboxylic acid compounds	AD
	AE entraining agent	Resinate anionic surfactant	
Water	Tap water	-	W

Table 2. Mix proportion of mortar (Experiment 1).

No.	W/C	Air (%)		Slump (cm)		s/a	Unit weight (kg/m^3)				
	(%)	Target range	Measured value	Target range	Measured value	(%)	C	W	S	G	AD
1	50	4.5 ± 1.5	4.5	18 ± 2.5	18.5	42.9	370	185	735	979	0.76
2	55		4.5		18.0	45.0	336		784	958	1.02
3	60		3.8		19.5	46.9	308		828	936	1.40
4	65		3.7		19.5	48.8	285		869	912	1.43

2.3. Experimental methods

2.3.1. Mixing and testing methods for fresh concrete

Fresh concrete was mixed according to the JIS A 1138 method of preparing test samples of concrete in laboratory. The slump was measured according to the JIS A 1101 test method for concrete slump. The air content was measured according to the JIS A 1128 method for testing the air content of fresh concrete by using a pressure-based method.

2.3.2. Bleeding test

Bleeding tests were conducted in accordance with the JCI-S-015-2018 method for testing the bleeding of concrete using a small container. The test was conducted twice for each level and the average value was taken as the bleeding amount.

2.3.3. Drilling test

For the drilling test, a small-diameter drilling tester (shown in Figure 1) was used. This testing machine uses two 14 N constant-load springs to press a diamond bit with a 2.8-mm diameter diamond bit against the test site and has a motor with a constant torque, which is operated at a constant revolution, to drill up to a depth of approximately 10 mm. The diamond particles adhering to the tip of the diamond bit are fine particles, and the diameter of the bit is almost constant at 2.8 mm, regardless of the sharpness of the bit. However, because the sharpness of the bit varies depending on the shape and arrangement of the diamond particles, the correction 3) described subsequently in this subsection is ensured.

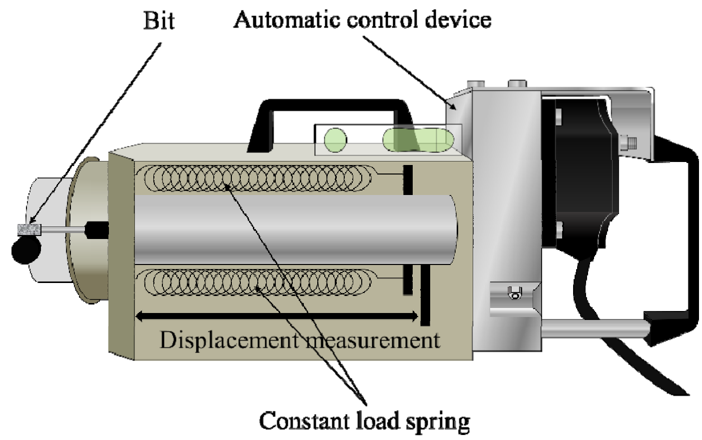

Figure 1. Small-diameter drilling tester.

Figure 2 shows the specimens used in the drilling test and their test positions. A cylindrical specimen with a diameter of 100 mm and a height of 200 mm was used for the drilling test. The shape and size of the specimens were determined based on the JCI-S-015-2018 method for testing the bleeding of concrete using a small container, and it was ensured that the specimen height is 212 ± 3 mm. The test specimens were hammered into a cylindrical polyvinyl chloride frame made of non-absorbent materials, which were neither affected by the cement nor deformed by the specimens. Each layer was poked 25 times with a stick and thereafter lightly tapped on the sides with a wooden hammer to compact them. After it was ensured that the surface was approximately at the same height of the formwork using a wooden trowel, the top surface was finished by pressing hard with a metal trowel, 5–6 h after the placement of the concrete, when the bleeding water had almost completely drained out and the specimen was hardened to the extent that it could not be deformed by pressing the specimen with a finger. After removal of the formworks, the specimens were cured in water until 28 days of age, and subsequently, cured in air at 20 °C until 91 days of age on the test day. Two specimens were tested per level, and each specimen was drilled at the location indicated by the red dot in Figure 2. Based on a previous report [6], the spacing between the drill tests in the figure is maintained at a specific distance such that it does not affect the adjacent drilling positions. As described below, a reference mortar made of fine aggregate (0.6 mm or less) was drilled before and after conducting the drilling tests of each level of specimens to correct the drilling speed.

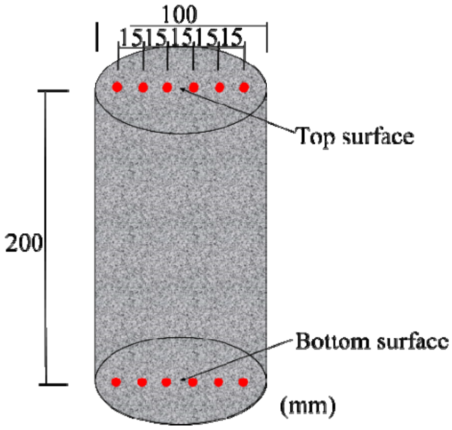

Figure 2. Test piece and test positions.

Figure 3 shows the flow for calculating and correcting the drilling speed, and Table 3 presents the symbols used in this report and their definitions. The methods for calculating and correcting the drilling speed are detailed as follows:

(1) Calculation of drilling speed

Figure 4 shows the relationship between the drilling speed and drilling depth as an example. The figure shows the results of a single drilling test, in which the drilling depths measured at 1/100 s intervals were averaged over 11 points and subsequently plotted at 1/25 s intervals. The drilling speed was extremely low in the area containing the aggregate; however, it was extremely high in the area containing voids and interfaces. In this experiment, the section where the cement paste was assumed to be mainly drilled was extracted. The red lines in the figure represent the areas where the extracted cement paste was mainly drilled, and the drilling speed for each hole was calculated by averaging these areas. Please refer to Table 3 for the extraction range of the drilling speed, V_p; for more details, please refer to Reference [3], where the extraction criterion for the drilling speed, V_p, was determined by comparing the relationship between the drilling speed and drilling depth (Figure 4; cross-sectional image of the drilled cross section). The drilling speed, V_p, for each surface is determined as illustrated in Figure 3. The drilling speed, V_p, of each measurement surface is the average value of 12 drilling speeds obtained by two specimens. Because the purpose of this study is to evaluate the quality of the polar surface layer, the values calculated within the range of the drilling depth, 0–5, were used in this study.

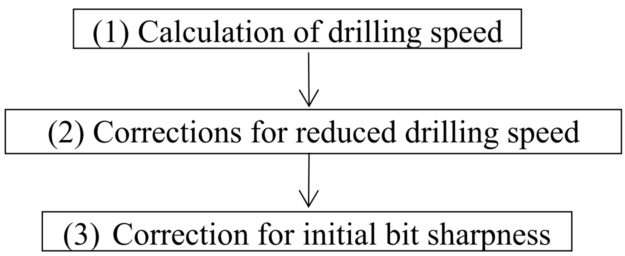

Figure 3. Flow of calculation and correction of drilling speed.

Table 3. Symbols used in this chapter and their definitions.

Symbol	Definition
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.

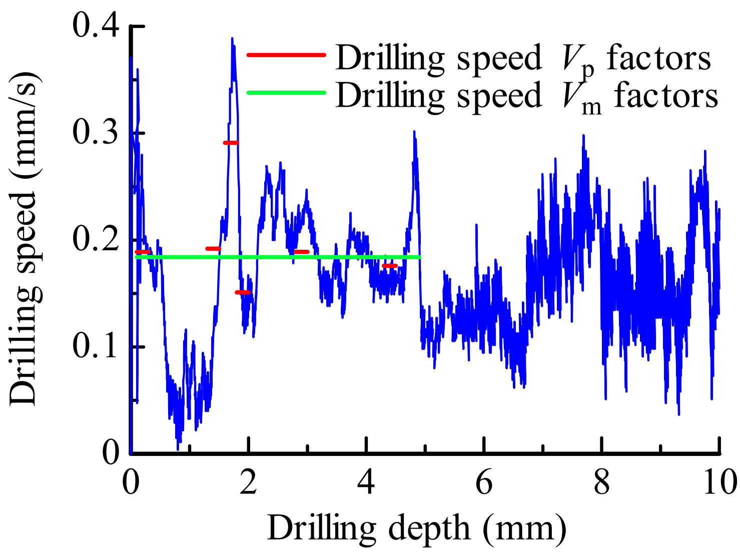

Figure 4. Example of the relationship between drilling speed and drilling depth (Experiment 1 W/C = 50%, bottom surface).

(2) Corrections for reduced drilling speed

The bit sharpness decreases almost linearly with the increase in the number of drillings, owing to the abrasion of diamond particles at the tip of the bit [3]. However, in practice, it is difficult to evaluate the degree of decrease in sharpness based on only the number of drilling times because diamond particles are significantly worn down after a long period of drilling in a hard, high-strength material. In this study, we conducted a drill test with one bit per two levels and corrected the drilling speed of each face obtained while calculating the drilling speed, assuming that the bit sharpness decreases linearly with the increase in the cumulative sum of the drilling depth and drilling time per hole. The bit sharpness at the start of the drilling test on a face was corrected for each measured face, assuming that the bit sharpness at the start of the drilling test on a face decreases with increase in the cumulative sum of the drilling depth and drilling time, up to the drilling test on the immediately preceding face.

(3) Correction for initial bit sharpness

The bit sharpness varies depending on the mounting direction (angle) and the variability of the bit itself [3]. To compare the drilling speeds between levels, the drilling speeds obtained (2) were corrected based on the ratio of the drilling speed, ${}_{r}V_{f}$, for the reference mortar drilled before the start of the drilling test at each level. The drilling speed, ${}_{r}V_{f}$, was based on a water-cement ratio of 50% in Experiment 1 and a unit water content of 170 kg/m^3 in Experiment 2.

In this report, the drilling speed, V_p, is defined as the drilling speed calculated and corrected by the above-described procedures (1)–(3), and the results of the experiments are discussed in the following subsections.

2.4. Experimental results and discussion

2.4.1. Influence of water-cement ratio on small-container bleeding amount

Figure 5 shows the change in the amount of small-container bleeding with time for each water cement ratio. As can be seen from the figure, there is an increase in the small-container bleeding amount up to 330 min of elapsed time at 50% and 55% water-cement ratio and up to 360 min of elapsed time at 60% and 65% water-cement ratio.

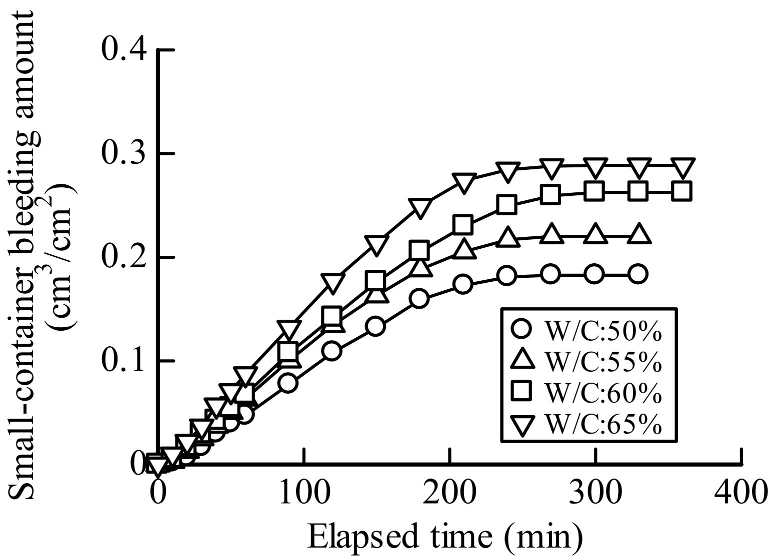

Figure 5. Relationship between small-container bleeding amount and elapsed time (Experiment 1).

Figure 6 shows the relationship between the small-container bleeding amount and the water-cement ratio. The absolute values of the correlation coefficient, r, and the regression equation are shown in the figure. For the regression equation, the linear regression was used, referring to the bleeding estimation equation in Reference [7] (the same applies to Figure 10). As shown in the figure, the small-container bleeding amount tends to increase as the water-cement ratio increases, and the correlation coefficient, *r*, shows a strong correlation between the small-container bleeding amount and the water-cement ratio.

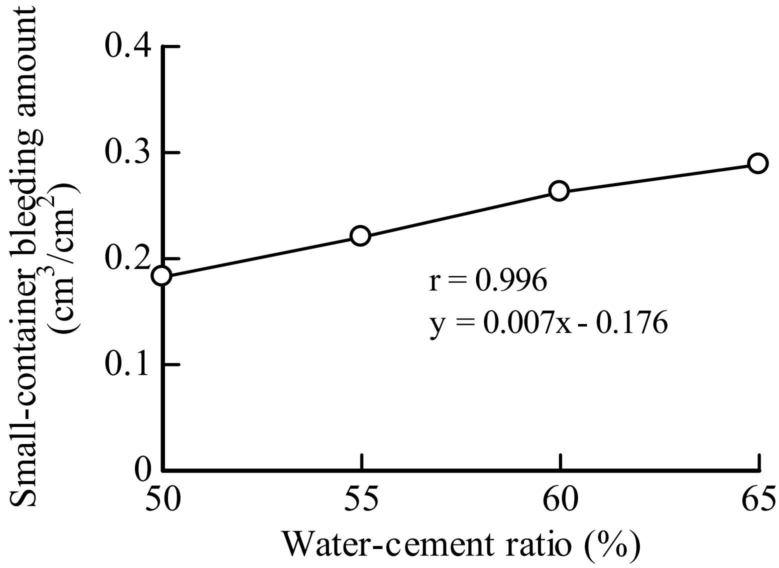

Figure 6. Relationship between small-container bleeding amount and water-cement ratio (Experiment 1).

2.4.2. Influence of water-cement ratio on drilling speed

Figure 7 shows the relationship between the drilling speed, V_p, and the water-cement ratio. The error bars in the figure are the average of the standard deviations of the pre-correction drilling speed for six holes drilled per specimen at each level (same for Figure 11). As shown in the figure, for the water-cement ratios of 50%, 55%, and 65%, the drilling speed, V_p, at the bottom surface is greater than the drilling speed, V_p, at the top surface; for a water-cement ratio of 60%, the drilling speed, V_p, at the top surface is greater than the drilling speed, V_p, at the bottom surface. The range of error bars for both the water-cement ratios is greater than the difference between the drilling speed, V_p, between the top and bottom surfaces. In general, it is considered that the bottom of the formwork is denser than the other areas. However, in this experiment, the difference between the top and bottom surfaces was small, and the drilling speed, V_p, was approximately equal. This may be because when the specimens are under the restraint of the formwork, mortar runoff occurs owing to the reduction in compaction, and gaps are maintained; therefore, the effect of gravity on the aggregate is small and material separation is less probable [8]. Moreover, the surface strength is significantly affected by the trowel finish when the amount of bleeding is large [9].

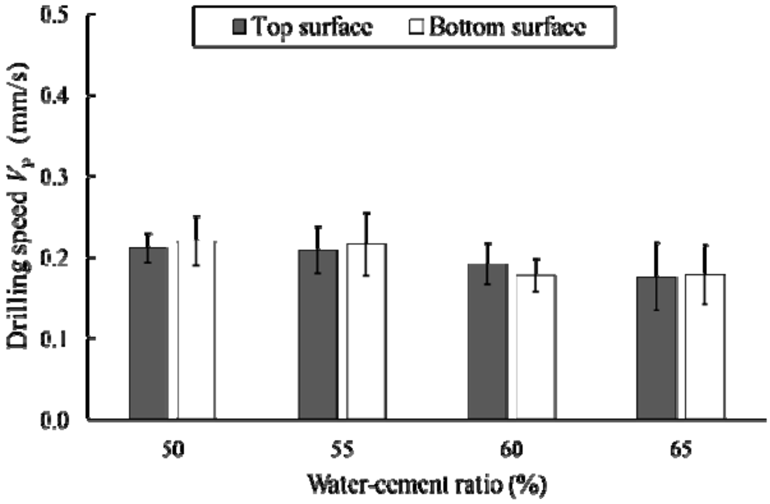

Figure 7. Relationship between drilling speed, V_p, and water-cement ratio (Experiment 1).

The drilling speed, V_p, decreased moderately as the water-cement ratio increased for both the top and bottom surfaces. This trend is opposite to that reported in a previous report on mortar specimens [5]. In an experimental study on the effects of changes in the coarse aggregate volume ratio on the bleeding rate, compressive strength, carbonated thickness, and air permeability of concrete, Yagawa et al. [10] reported that as the coarse aggregate volume ratio increased, the compressive strength of concrete and wet-screened mortar decreased, and the carbonated thickness and air permeability increased. In this study, the influence of coarse aggregate volume was more prominent than that of the water–cement ratio in the design of the mix proportion conditions where the coarse aggregate volume increased as the water-cement ratio decreased. However, from general knowledge [3,5], there is also a conflicting trend. Meanwhile, based on the results of previous studies, the drilling speed has been calculated by extracting the areas that are considered to have been drilled mainly with cement paste; however, at present, no method has been established to completely exclude the results of drilling through fine aggregate finer than the diameter of the drill bit. Therefore, we cannot deny the possibility that the results may be affected by the amount of fine aggregate contained in the test piece. In this experiment, the amount of fine aggregate increased with increasing water-cement ratio. Because it can be easily predicted that the drilling speed decreases when fine aggregate is drilled, the experimental results suggest that the effect of the volume of fine aggregate is greater than that of the water-cement ratio. In other words, there is a possibility that it can be used for not only estimate strength but also evaluate surface quality of concrete by examining in detail the method for calculating and correcting the drilling speed and eliminate the influence of fine aggregate.

2.4.3. Relationship between drilling speed and small-container bleeding amount

Figure 8 shows the relationship between the drilling speed, V_p, and the small-container bleeding amount. The absolute values of the correlation coefficient, r, and the regression equation are shown in the figure. For the regression equation, a logarithmic regression was used, referring to the relationship between the drilling speed and air permeability rate described in a previous report [5] (this also applies to Figure 12). As shown in the figure, the drilling speed, V_p, tends to decrease gradually as the small-container bleeding amount increases. The relationship between the water and cement ratio and the drilling speed, V_p, is considered to have a strong influence on this. How much the difference in bleeding amount actually deteriorated the quality of the concrete surface is outside the scope of this experiment. However, as mentioned above, drilling speed is also affected by the amount of fine aggregate. In the future, more detailed studies the drilling speed are needed.

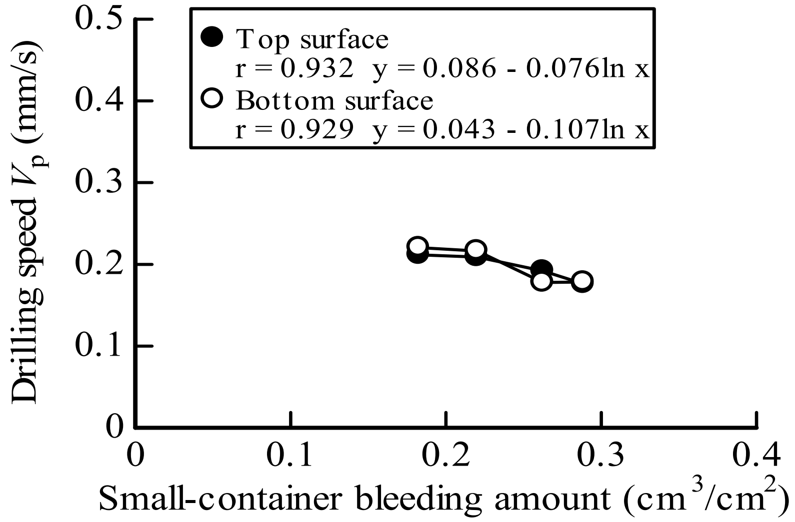

Figure 8. Relationship between drilling speed, V_p, and small-container bleeding amount (Experiment 1).

3. Influence of unit water content on bleeding amount and drilling speed (Experiment 2)

3.1. Experimental factor

The experimental factor, the unit water content, was considered. The unit water content was set at four levels: 170, 175, 180, and 185 kg/m^3.

3.2. Materials and mix proportion of concrete

The materials used for the concrete were the same as those used in Experiment 1. Table 4 shows the mix proportions of the concrete. The water-cement ratio was the same for all the cases; this facilitated clarifying the influence of the unit water content. Similar to Experiment 1, the air content (4.5 ± 1.5%) and slump (18 ± 2.5 cm) were adjusted by the amount of unit chemical admixture to ensure that it is within a certain range.

Table 4. Mix proportion of mortar (Experiment 2).

No.	W/C (%)	Air (%)		Slump (cm)		s/a (%)	Unit weight (kg/m^3)				
		Target	Measured	Target	Measured		C	W	S	G	AD
1	55	4.5 ± 1.5	4.5	18 ± 2.5	17.5	46.8	309	170	844	958	2.48
2			4.5		17.0	46.2	318	175	823		1.60
3			4.3		18.0	45.7	327	180	805		1.32
4			4.5		18.0	45.0	336	185	784		1.02

3.3. Experimental methods

The experimental method was the same as that in Experiment 1.

3.4. Experimental results and discussion

3.4.1. Influence of unit water content on the small-container bleeding amount

Figure 9 shows the change in the small-container bleeding amount per unit water content over time. As can be seen from the figure, up to 270 min of elapsed time, the final small-container bleeding amount is generally the same for every mix proportion, although the small-container bleeding amount tends to increase as the unit water content increases. The bleeding test completion time tends to be shorter as the unit water content increases. This result is attributed to the impact of the difference in the setting time and the hydration reaction rate depending on the amount of unit chemical admixture.

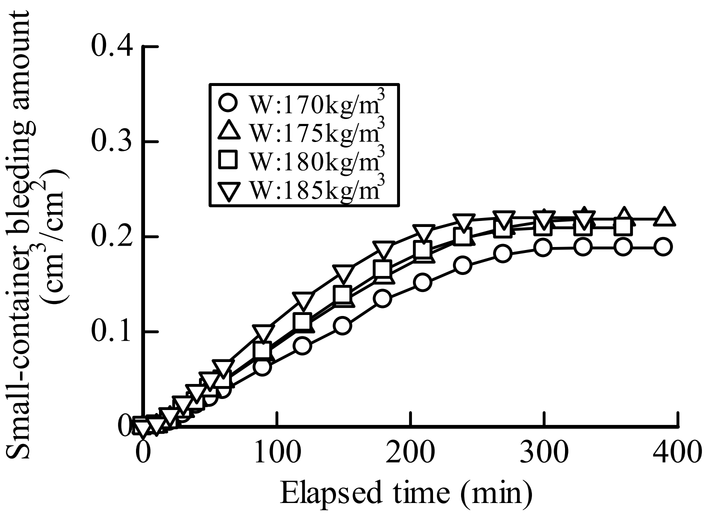

Figure 9. Relationship between small-container bleeding amount and elapsed time (Experiment 2).

Figure 10 shows the relationship between the small-container bleeding amount and the unit water content. As shown in the figure, the small-container bleeding amount tends to increase gradually as the unit water content increases; however, the difference in case of the unit water content is small.

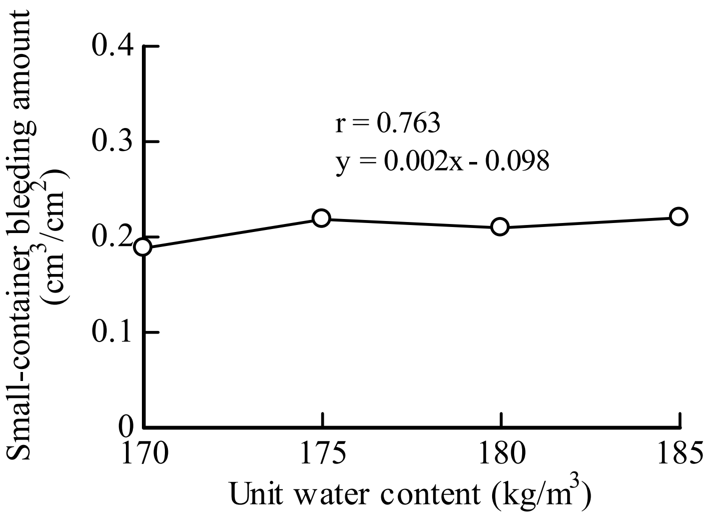

Figure 10. Relationship between small-container bleeding amount and unit water content (Experiment 2).

3.4.2. Influence of unit water content on drilling speed

Figure 11 shows the relationship between the drilling speed, V_p, and the unit water content. As can be seen from the figure, at the unit water content values of 170 and 175 kg/m^3, the drilling speed V_p, at the bottom is greater than the drilling speed, V_p, at the top surface. Furthermore, at unit water content values of 180 and 185 kg/m^3, the drilling speed, at the bottom surface is less than the drilling speed, V_p, at the top surface, and there is no specific trend in the drilling speed, V_p, between the bottom and top surfaces. This is because, similar to that obtained in Experiment 1 (in addition to the suppression of segregation owing to the constraint of the formwork), the differences in the surface quality caused by the difference in the unit water content and the influence of the degree of trowel-finishing on the hammering surface are considered to be distinct.

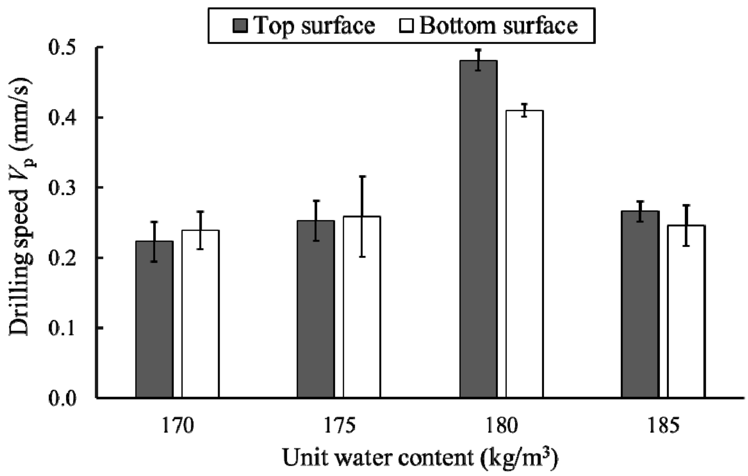

Figure 11. Relationship between drilling speed, V_p, and unit water content (Experiment 2).

As shown in the figure, the drilling speed, V_p, for a unit water content of 180 kg/m^3 is significantly higher than that at the other levels. As shown in Table 5, the drilling speed, $_rV_f$, of the bits used to drill the test specimens for the water content of 180 kg/m^{3}was significantly lower than those, for the other levels, as indicated by the $_rV_f$ of the bits used in this experiment. Correction between the bits with different sharpness is essential for the comparison between levels. Therefore, when the sharpness of the bit differs significantly between levels, similar to that in this experiment, careful consideration of the correction and evaluation methods of the drilling speed is necessary.

Furthermore, the drilling speed, V_p, tends to increase moderately as the unit water content increases, except for the unit water content of 180 kg/m^3. However, the difference in drilling speed between the levels is small. This is because the same water–cement ratio that governs the strength and hardened structure, contributes more to the drilling speed, V_p, than the unit water content, considering that the drilling speed, V_p, is the speed at which the cement paste is considered to be drilled. As shown in Table 4, the volume of fine aggregate in the specimen decreased with increasing unit water content in experiment 2. Therefore, the possibility that the difference in the unit water content was not clear due to the increase in the drilling speed as the fine aggregate volume decreased needs to be considered.

Table 5. Each level of rV_f in Experiment 2.

Unit water content (kg/m^3)	170	175	180	185
rV_f	0.217	0.236	0.099	0.206

3.4.3. Relationship between drilling speed and small-container bleeding amount

Figure 12 shows the relationship between the drilling speed, V_p, and the small-container bleeding amount. As shown in the figure, the drilling speed, V_p, (0.481 mm/s for the top surface and 0.409 mm/s for the bottom surface) for a unit water content of 180 kg/m^3, is remarkably high for the reasons mentioned above; however, at the other levels, the drilling speed, V_p, tends to increase moderately as the small-container bleeding amount increases. However, the difference in the drilling speed, V_p, with the small-container bleeding amount is small.

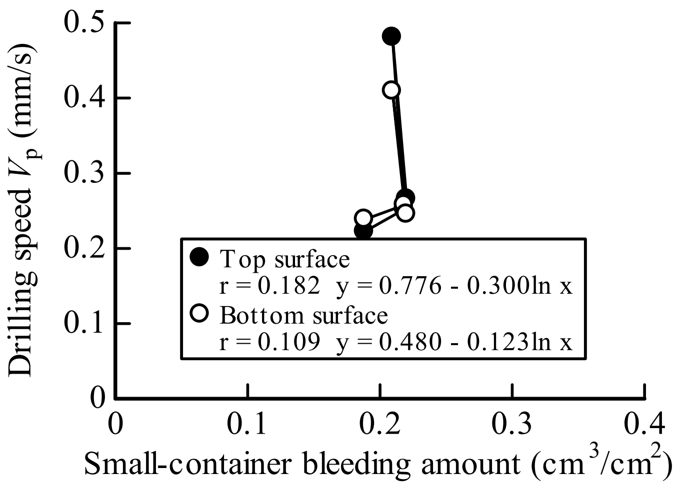

Figure 12. Relationship between drilling speed, V_p, and small-container bleeding amount (Experiment 2).

4. Conclusion

In this study, the influence of the bleeding of concrete due to the mix proportion on the drilling speed of the hardened surface layer was investigated. The influence of bleeding on the drilling speed of the specimen surface was also discussed based on the test results of the top and bottom surfaces.

The findings of this experimental study can be summarized as follows:

(1) The drilling speed V_p changes depending on the water-cement ratio and the unit water content.
(2) The amount of bleeding affects the drilling speed, but the drilling speed is affected by the volume of the fine aggregate in the specimen.
(3) There is a possibility that it can be used for surface quality evaluation of concrete by examining in detail the method of correcting the drilling speed V_p.

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Conflict of interest

The authors declare no conflicts of interest for this study.

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