Study on Detection of Filling and Compaction Based on Electrical and Vibrational Characteristics of Fresh Concrete

T. Yamada[1*], Y. Umino[2], and T. Iyoda[3]

[1] *Toda Corporation, Tokyo, Japan*

Email: tsutomu.yamada@toda.co.jp
[2] *Munekata Industrial Machinery, Fukushima, Japan*

Email: yumino_trd@munekata.co.jp
[3] *Shibaura Institute of Technology, Tokyo, Japan*

Email: iyoda@sic.shibaura-it.ac.jp

ABSTRACT

Visual monitoring of the progress of concrete filling and compaction at the crown area in a tunnel lining is generally impossible because all inspection windows and bulkhead forms are closed. This situation may result in void generation at the upper part of the crown area due to remaining air or bleeding water. Therefore, we devised an innovative sensor to detect concrete filling and compaction along the length of the crown area. This sensor features a long, thin sheet on which multiple detection components and associated wires are placed. The purpose of this study is to detect filling and compaction using the sensor and understand the electrical and vibrational characteristics of fresh concrete. We determined the sensor requirements for filling detection by identifying fresh concrete, bleeding water and air. The differences between their electrical characteristics make it possible to identify these materials. The filling detectors consist of a pair of electrodes arranged in parallel. Measurements of fresh concrete, bleeding water, and air showed that the sensor could identify these differences. Furthermore, we investigated the factors that affect these electrical characteristics and concluded that there is a strong relationship between the electrical impedance and the cement paste volume, except for that absorbed around aggregates. In contrast, for compaction, it is necessary to detect high-frequency waves derived from an internal vibrator. We use the functionality of a piezoelectric material that converts deformations caused by waves propagating in fresh concrete into electricity. The compaction detectors consist of piezoelectric membranes that are sandwiched between electrode membranes. Experimental results obtained with a mock-up sensor using these detectors demonstrated that it could predict the degree of compaction. The results indicated that the sensor will enable production of promising high-quality concrete linings because it monitors the progress of concrete filling and compaction along the entire tunnel crown length.

KEYWORDS: *Sensor, Fresh concrete, Electrical characteristics, Vibrational characteristics*

1. Introduction

The New Austrian Tunneling Method (NATM) is a conventional tunneling method that has been applied to numerous mountain tunnels in Japan. After excavation, shotcreting, rock bolting, and waterproofing are implemented in sequence, concrete is then placed using forms consisting of steel panels, framed structures, gantries, and other components. During placement of concrete into the side wall sections, a worker monitors the procedure and quality visually using the inspection windows installed on these forms. However, it is impossible to monitor the behavior of the concrete in arch sections because the upward injection method is applied to these sections and all inspection windows are subsequently closed. Therefore, the achievement of concrete filling in the arch sections is judged through reference to the differences between scheduled and actual quantities, and via the leakage of mortar or bleeding water from the bulkheads of the forms. In addition, specific vibrators for the arch section, such as the pulling-out vibrator system, have been used widely for at least a decade in Japan. However, it is quite difficult to confirm the propagation of vibrations in the arch sections while the concrete is compacted by such a vibrator. Under these conditions, voids in the upper parts of the crown areas, cold joints, and color irregularities in the arch sections have sometimes occurred.

Therefore, conventional sensors to monitor the filling and compaction of concrete are gradually being applied to the upper part of the crown area. The sensors that monitor concrete filling use methods based on discharges between electrodes, as developed by Hirata and Sogo (1996), the capacitance between cables, as developed by Fujikura (2012), and optical detection using light-emitting diodes and sensor diodes, as proposed by Sakai et al. (1995). A sensor that is used to monitor both filling and compaction of concrete using both the piezoelectric effect and the inverse piezoelectric effect of a piezoceramic device was developed by Kaneko et al. (2009). These conventional sensors, which can only monitor one spot, are not suitable for monitoring the entire length of a segment of a lining concrete placement. It would be necessary to set multiple sensors and cables in the upper part of the crown area to monitor the entire length of the lining concrete placement. Such setting would require complex operations. As a result, only a few sensors have been used for each concrete placement.

We devised an innovative sensor to detect the filling and compaction of fresh concrete along the entire length of the crown area. Figure 1 shows a schematic illustration of the proposed sensor. This sensor incorporates multiple detection components with associated wires into a base sheet. This paper reports the results of fundamental experiments performed with this sensor to confirm its applicability.

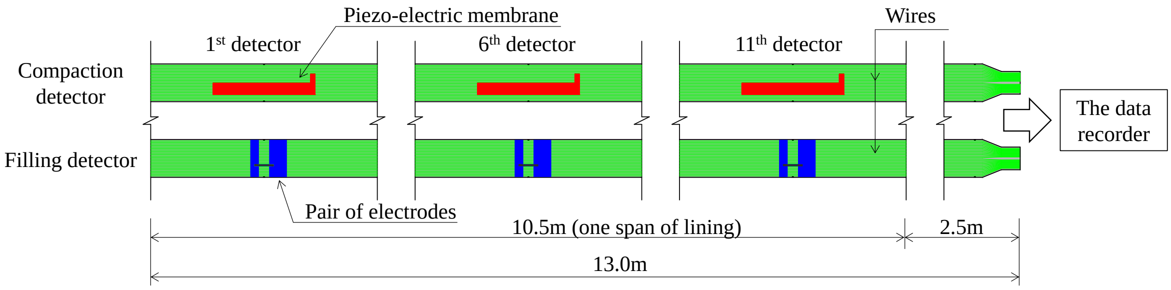


Figure 1. Schematic illustration of the sensor

2. Developed sensor system

The fundamental function requirement for the proposed sensor is an ability to monitor both filling and compaction of fresh concrete. Figure 2 shows a cross-sectional diagram of the proposed sensor. Electrodes are set on the concrete side and piezoelectric elements are set on the waterproof sheet side of the base sheet (which is approximately 0.1 mm thick).

The electrodes, piezoelectric elements, and wires all have a thickness of the order of 0.01 mm. All wires are set on the waterproof sheet side of the base sheet and are covered using an insulation layer (0.4 mm thick) that doubles as an adhesion layer. As a result, the sensor structure is simplified, as shown in Figure 3, and is 0.6 mm thick in total. The workability of setting the proposed sensor onto a waterproof sheet is easier than it is for conventional sensors.

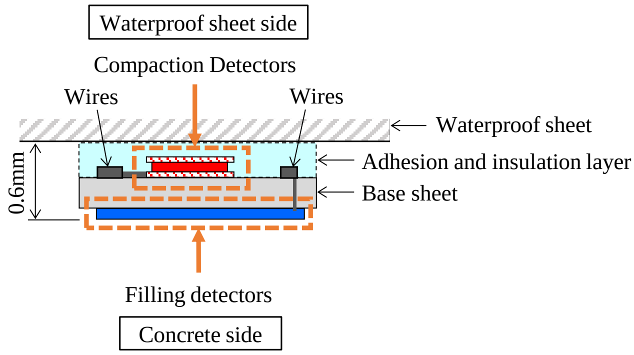


Figure 2. Cross-sectional diagram of the sensor

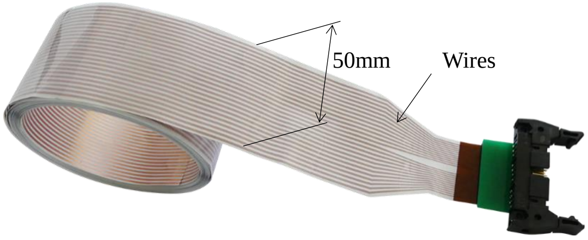


Figure 3. Form of the sensor

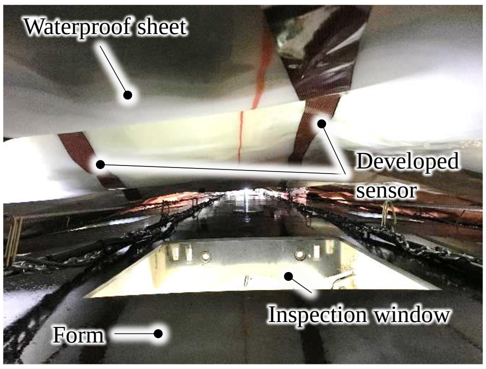


Figure 4. Example of installation of the sensor

Figure 5. Data recorder

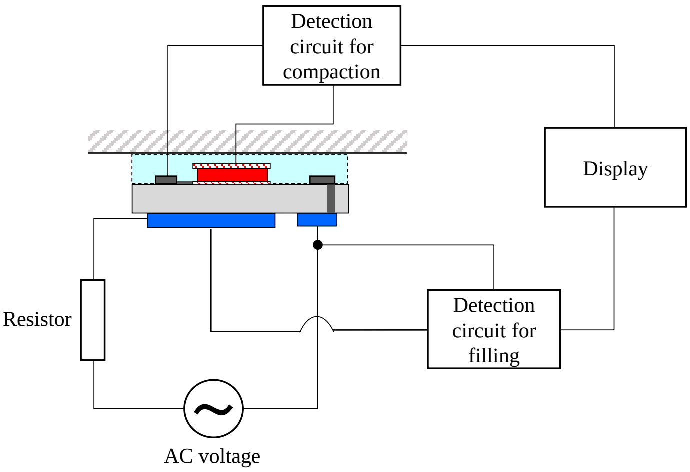


Figure 6. Block diagram of the sensor system

Figure 4 shows an example of installation of the proposed sensor in the upper part of the crown area of the lining. This sensor can include 11 detectors for filling and compaction in one lining segment. Therefore, the sensor can monitor both processes simultaneously along the entire length of the segment. Figure 5 shows the data recorder used and its display. The sensor is connected to the data recorder via a length of cable. The data recorder analyzes the signals from the sensor and subsequently predicts the processes of filling and compaction using a threshold based on experiments performed with the system illustrated in Figure 6. In addition, it will be possible to monitor the entire area of the upper part of the tunnel lining if multiple detectors are placed closely together on the base sheet.

3. Background on detection of concrete

3.1 Requirements and theory

We determined the sensor requirements for filling detection by identifying concrete, bleeding water, and air. The differences in the electrical characteristics of these substances make it possible to identify the materials. In particular, concrete must be identified separately from bleeding water. Attention should be paid to the possibility that large amounts of bleeding water can gather in the upper part of the concrete lining placement. Bleeding water left in this upper area can generate air voids and lead to weakened portions of the lining. Therefore, it is necessary to continue concrete placement using the upward injection method until all bleeding water is removed from the form bulkheads.
The liquid phases of fresh concrete and bleeding water include cations, e.g., Na^+, K^+, and Ca^{2+}, along with anions such as OH^- that dissolve from the cement. Because of these ionic carriers, both fresh concrete and bleeding water exhibit conductivities after voltages are applied to these materials. Madhavi and Annamalai (2016) concluded that the electrical conductivity method represents an effective and reliable method for assessment of the various characteristics of concrete. From this perspective, these electrical characteristics can be used effectively to monitor the filling of concrete in the arch sections.

3.2 Comparison between electrical impedance and output delivered by the developed sensor

Figure 7 shows an illustration of the detectors for sensing of the filling of fresh concrete. These detectors consist of a pair of electrodes arranged in parallel. The data recorder can monitor the voltage between these electrodes after the voltage is applied to a circuit coupled with the electrodes and a resistor. Furthermore, to process the voltage data programmatically, the data recorder delivers a 10-bit digital output signal (hereafter called "the digital output") that is converted from the original analog voltage. This digital output will change when either fresh concrete or bleeding water contacts the electrodes. By monitoring changes in the digital output, we can then programmatically identify casting transitions while casting the concrete.
Table 1 shows the mixture proportions, with mortar included as a reference. The water-cement ratios of the mortar and the bleeding water were set widely to range from 30% to 100%, except for the range in which the bleeding water cannot be removed. These specimens are poured up to a height of 50 mm into a plastic vessel, which is 215 mm long and 145 mm wide, as shown in Figure 8. An impedance analyzer (IM3570; HIOKI EE corporation, Ueda, Nagano, Japan) was also used to validate the sensor. A series of digital outputs from the developed sensor and electrical impedance values from the impedance analyzer were measured using a 5 V rms signal at 1 kHz.

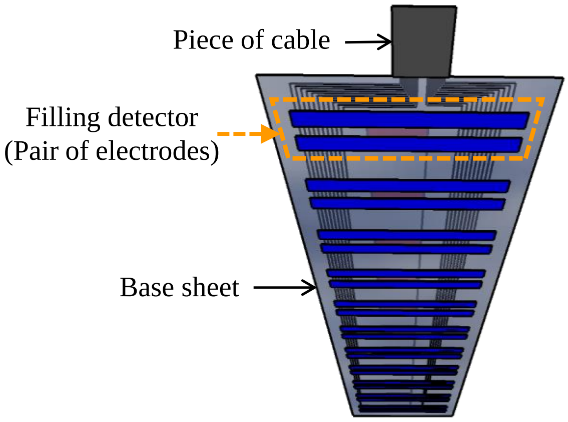


Figure 7. Illustration of the filling detectors

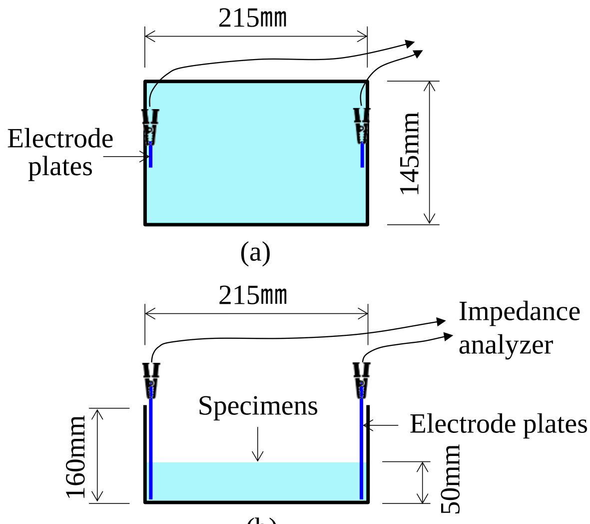
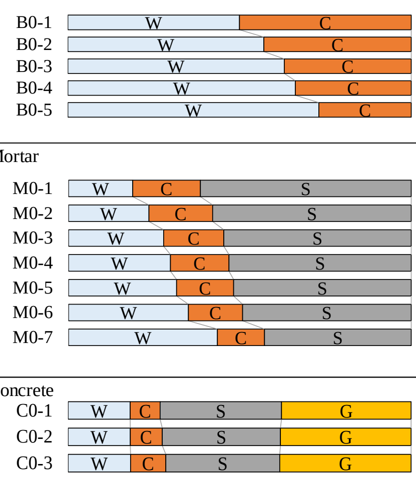


Figure 8. Schematic illustration of the experiment: (a) plan view, and (b) side view

Table 1 Mixture proportions.

No.	W/C ratio by wt.%	s/a ratio by wt.%	S/C ratio by wt.	Unit weight, kg/m^3				Volume composition
				Water	Cement	Fine agg.	Coarse agg.	
B0-1	50	-	-	612	1224	0	0	Bleeding water
B0-2	55	-	-	635	1154	0	0	
B0-3	60	-	-	654	1090	0	0	
B0-4	70	-	-	689	984	0	0	
B0-5	100	-	-	759	759	0	0	
M0-1	30	100.0	2.5	179	596	1503	0	Mortar
M0-2	40	100.0	2.5	224	561	1416	0	
M0-3	50	100.0	2.5	265	530	1336	0	
M0-4	55	100.0	2.5	284	516	1300	0	
M0-5	60	100.0	2.5	301	502	1267	0	
M0-6	70	100.0	2.5	334	477	1203	0	
M0-7	100	100.0	2.5	415	415	1047	0	
C0-1	68.3	48.4	3.5	173	253	879	982	Concrete
C0-2	63.8	47.5	3.2	173	271	855	990	
C0-3	58.2	46.4	2.8	174	299	824	996	



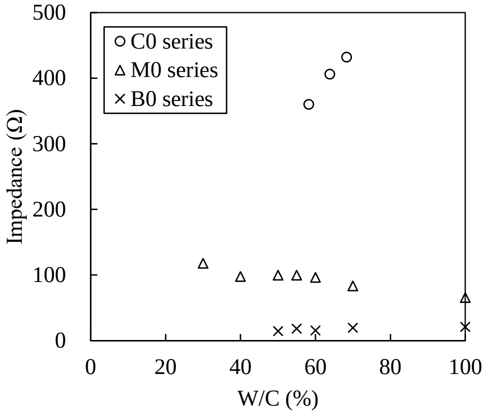


Figure 9. Electrical impedance measured using the impedance analyzer versus water-cement ratio

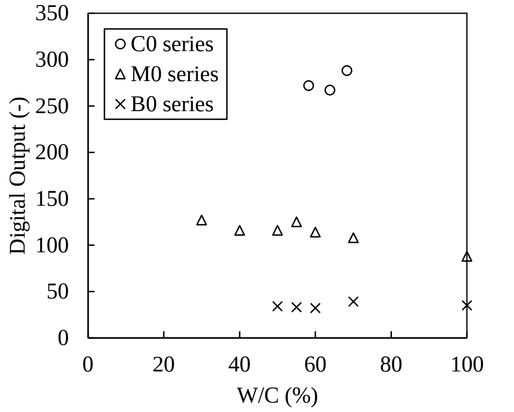


Figure 10. Digital output measured by the filling detector versus water-cement ratio

Table 2 Mixture proportions.

No.	W/C ratio by wt.%	s/a ratio by wt.%	S/C ratio by wt.	Unit weight, kg/m^3				Volume composition
				Water	Cement	Fine agg.	Coarse agg.	
P-1	20	-	0.0	387	1935	0	0	
P-2	30	-	0.0	486	1620	0	0	
P-3	40	-	0.0	558	1395	0	0	
P-4	50	-	0.0	612	1224	0	0	
P-5	60	-	0.0	654	1090	0	0	
P-6	70	-	0.0	689	984	0	0	
P-7	100	-	0.0	759	759	0	0	
P-8	1,000	-	0.0	969	97	0	0	
P-9	10,000	-	0.0	997	10	0	0	
P-10	100,000	-	0.0	1000	1	0	0	
M1-1	40	100.0	1.7	273	683	1195	0	
M1-2	50	100.0	2.0	299	598	1195	0	
M1-3	60	100.0	2.2	320	533	1195	0	
M1-4	70	100.0	2.5	336	480	1195	0	
M2-1	50	100.0	3.0	241	482	1440	0	
M2-2	50	100.0	2.5	267	534	1331	0	
M2-3	50	100.0	2.0	299	598	1195	0	
M3-1	55	100.0	5.0	186	338	1695	0	
M3-2	55	100.0	3.0	258	469	1405	0	
M3-3	55	100.0	1.0	418	760	758	0	
C1-1	58	33.6	3.1	126	217	663	1354	
C1-2	58	41.5	3.1	148	255	778	1130	
C1-3	58	50.6	3.1	170	293	896	903	
C1-4	58	60.7	3.1	192	331	1014	676	
C1-5	58	72.1	3.1	214	369	1129	451	
C2-1	55	30.0	1.6	175	318	522	1254	
C2-2	55	40.0	2.2	175	318	696	1074	
C2-3	55	50.0	2.7	175	318	870	895	
C2-4	55	60.0	3.3	175	318	1044	715	
C2-5	55	70.0	3.8	175	318	1216	536	
C3-1	50	47.6	2.2	185	370	796	903	

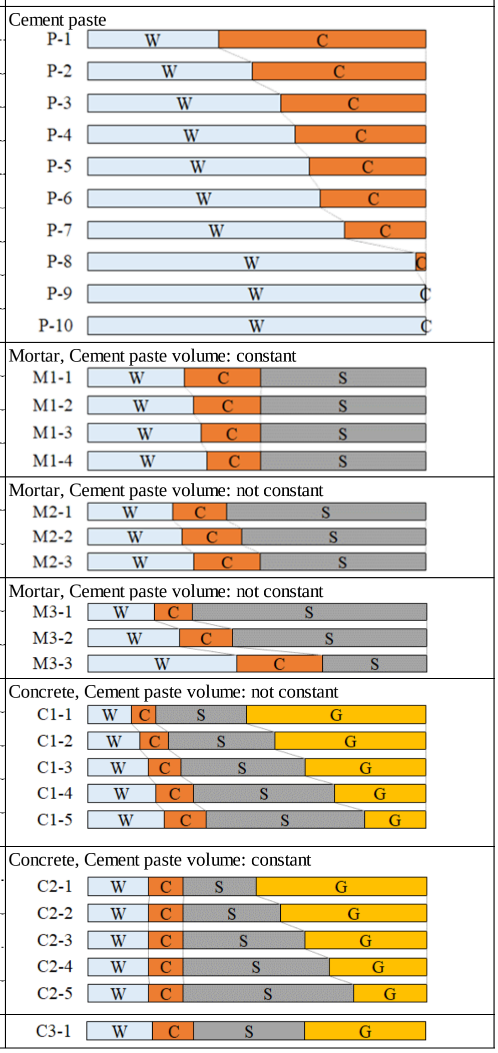


Figure 9 presents the electrical impedance results obtained with the HIOKI IM3570 impedance analyzer. The electrical impedances ranged from 360 Ω to 432 Ω for fresh concrete, from 66 Ω to 118 Ω for fresh mortar, and from 15 Ω to 21 Ω for the bleeding water. These electrical impedance ranges were grouped without overlaps. Figure 10 presents the digital output results acquired with the developed sensor. The digital outputs ranged from 267 to 288 for fresh concrete, from 88 to 127 for fresh mortar, and from 32 to 39 for the bleeding water. Furthermore, the impedance analyzer delivered an electrical impedance of 480 MΩ for air, which was much higher than that of fresh concrete. The data recording of air delivered a value of 930 on the digital output, which was 3.2–3.5 times that of the value for fresh concrete. These digital output ranges were grouped along with those for the electrical impedance. The feasibility of the sensor was thus verified successfully using the results from the impedance analyzer.

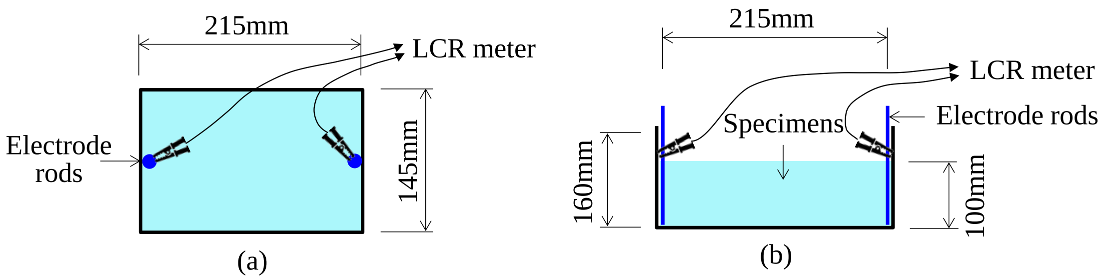


Figure 11. Schematic illustration of the experiment: (a) plan view, and (b) side view

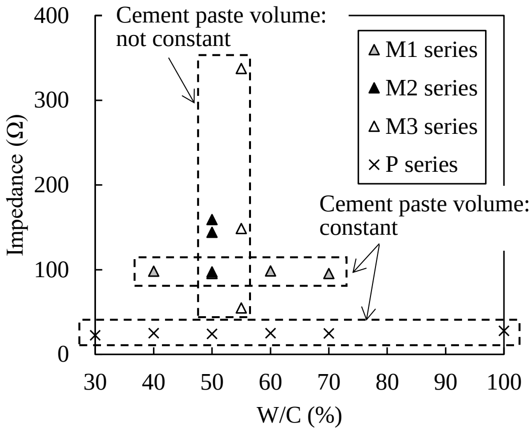


Figure 12. Electrical impedance measured using the LCR meter versus water-cement ratio

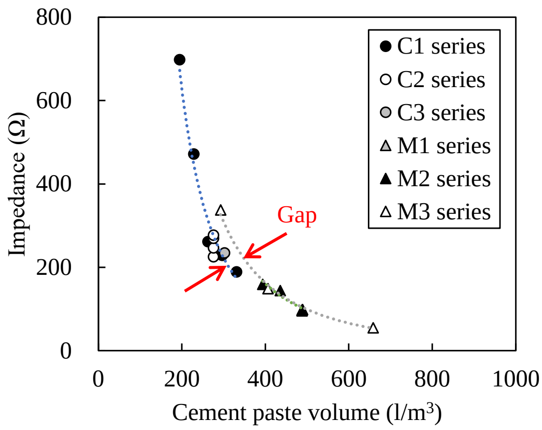


Figure 13. Electrical impedance measured using the LCR meter versus cement paste volume

3.3 Exploratory investigation of the effects of mixture proportions

From the results shown in Figure 9, it can be reasoned that the existence of aggregates in the materials affected their electrical characteristics more than either the water-cement ratio or the unit water content. The tendencies shown in these results corresponded with previous experimental results obtained by Ota and Iyoda (2015) with regard to comparison of the electrical resistance characteristics of concrete and cement paste. To reveal the factors that affect the electrical characteristics of concrete, we measured the electrical impedance using an inductance-capacitance-resistance (LCR) meter (IM3536; HIOKI EE corporation, Ueda, Nagano, Japan) and a variety of mixture proportions, as listed in Table 2. These mixtures were poured up to a height of 100 mm into the plastic vessel, as shown in Figure 11.

Figure 12 shows the electrical impedance characteristics of cement paste and mortar versus the water-cement ratio. The electrical impedances of the P and M1 series (cement paste volumes: constant) were constant. This means that the electrical impedances of both cement paste and mortar have no significant correlation to either the water-cement ratio or the unit water content. In contrast, the electrical impedances of the M2 and M3 series (cement paste volumes: not constant) varied relative to the fine aggregate or cement paste volumes. We thus focused on the cement paste volume, in which ionic carriers can move.

Figure 13 shows the electrical impedance characteristics versus cement paste volume. The results appear to show that the cement paste volume has a good relationship with the impedance. However, a gap was found between the fitted curves for mortar and concrete. The difference between mortar and concrete is the presence of coarse aggregate in concrete, which has a smaller specific surface area than fine aggregate. Therefore, we attribute the slight changes in the electrical impedance caused by the type of aggregate to cement paste being absorbed around the aggregates, which then cannot contribute to the ionic movements. Figure 14 shows an image of this hypothesis. The cement paste volume, with the exception of that absorbed around the aggregates (hereafter called "effective cement paste volume"), which contributes to the ionic movement can be described using:

$$V_{\mathrm{eff}} = V_{\mathrm{P}} - \alpha\, SA \tag{1}$$

where V_{eff} is the effective cement paste volume (l/m^3), V_{P} is the cement paste volume (l/m^3), α is a coefficient (mm), and SA is the surface area of the aggregate (m^2/m^3). In the aggregate used in this study, the most appropriate value of α is 0.005 mm. The SA was calculated by addition of the combination of the products of the unit aggregate content and the specific surface area for both the fine aggregate and the coarse aggregate, which are based on their particle size distributions.

Figure 15 shows that the measured electrical impedances basically have a strong relationship with effective cement paste volume, except for the gap shown in Figure 13. Additionally, a linear fit with a coefficient of determination equivalent to 0.934 was obtained to relate the electrical impedance to the effective cement paste volume when taking the logarithm of both sides in Figure 16. It is therefore possible that the sensor with the two electrodes using this relationship detects not only the filling of concrete, but also the degree of material segregation in the concrete. However, there is room for further investigation to add a function for detection of material segregation to the sensor system.

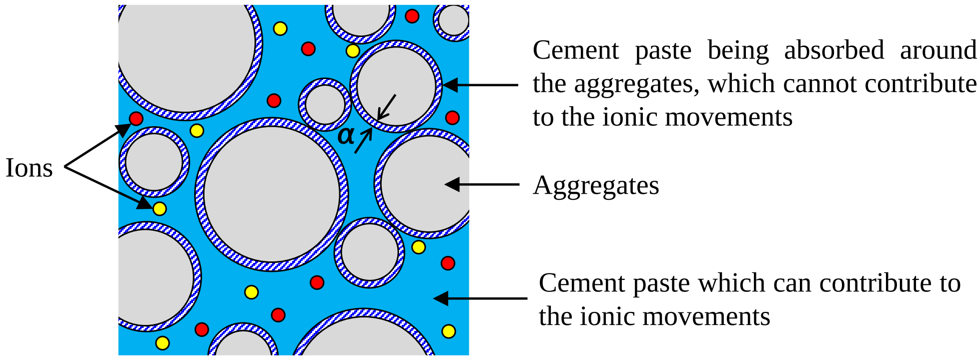


Figure 14. Image of hypothesis that cement paste absorbed around aggregates does not contribute to the ionic movements in the cement paste

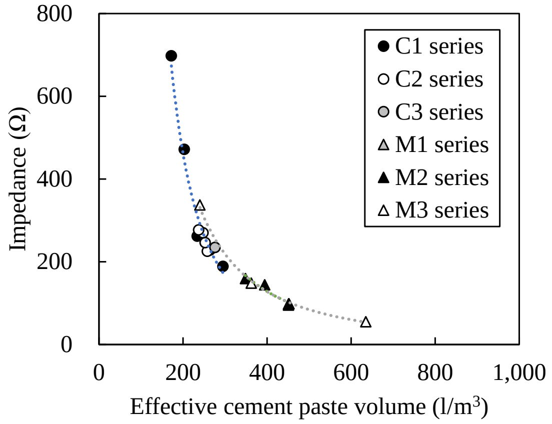


Figure 15. Electrical impedance measured using the LCR meter versus effective cement paste volume

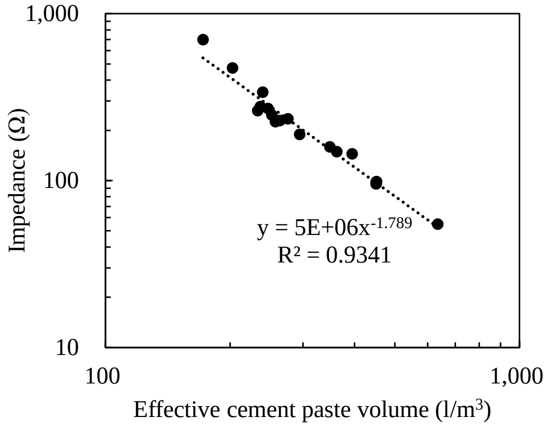


Figure 16. Relationship between electrical impedance and effective cement paste volume

4. Background on detection of vibration

4.1 Requirement and theory

An internal vibrator with high-frequency waves at between 200 Hz and 240 Hz was used to compact the fresh concrete. Iwasaki and Sakamoto (1989) reported that the voltage amplitude decreased after such waves propagated in fresh concrete, although their frequency did not change greatly. Therefore, it is necessary to detect waves that have the above characteristics and are effective for detection of the compaction of fresh concrete.

We use the functionality of a piezoelectric material that converts deformation into electricity. Use of either paste spray coating or paste painting techniques allowed us to create piezoelectric membranes with arbitrary shapes, although the shapes and elements available for conventional piezoelectric materials were limited. Figure 17 shows an illustration of the detectors for sensing of compaction of fresh concrete. The compaction detector, which consists of a piezoelectric membrane sandwiched between electrode membranes, generates electricity that is derived from waves from the internal vibrator propagating in the fresh concrete. The program in the data recorder judges the degree of compaction of the fresh concrete based on the voltage frequency, the voltage amplitude, and the detection time.

4.2 Experimental results on vibration propagation

Figure 18 shows an experiment performed with a wooden mock-up that was 400 mm wide, 500 mm high, and 10.5 m long. A waterproof sheet consisting of a 0.8-mm-thick waterproof membrane with a 3-mm-thick back buffer material was installed on the interior surface. We simulated the upper part of the tunnel lining using the wooden mock-up. The sensor used in the experiment was a long sensor containing 11 compaction detectors, which were 10 mm wide, 60 mm long, and were installed at the center of the interior of each section. We measured the vibrations from the internal vibrator, which had a diameter of 52 mm and output frequency of 200 Hz, as they propagated in the fresh concrete immediately after casting the concrete with the proportions shown in Table 3. The insertion positions of the internal vibrator were at 30 mm, 100 mm, and 300 mm intervals between the detector and internal vibrator locations.

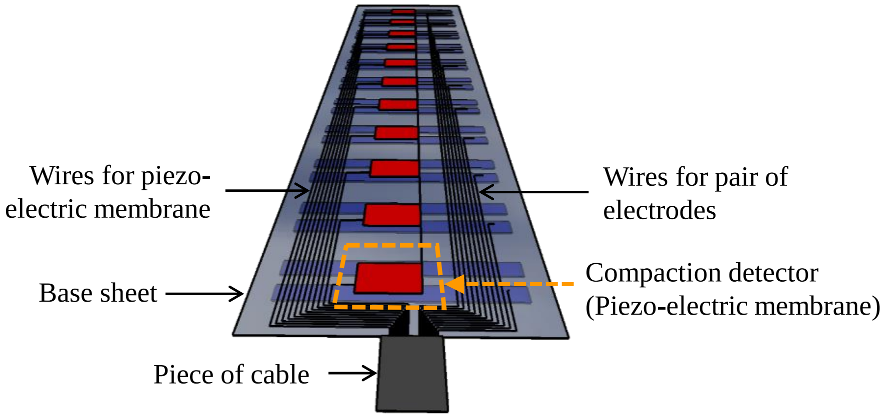


Figure 17. Illustration of the compaction detectors

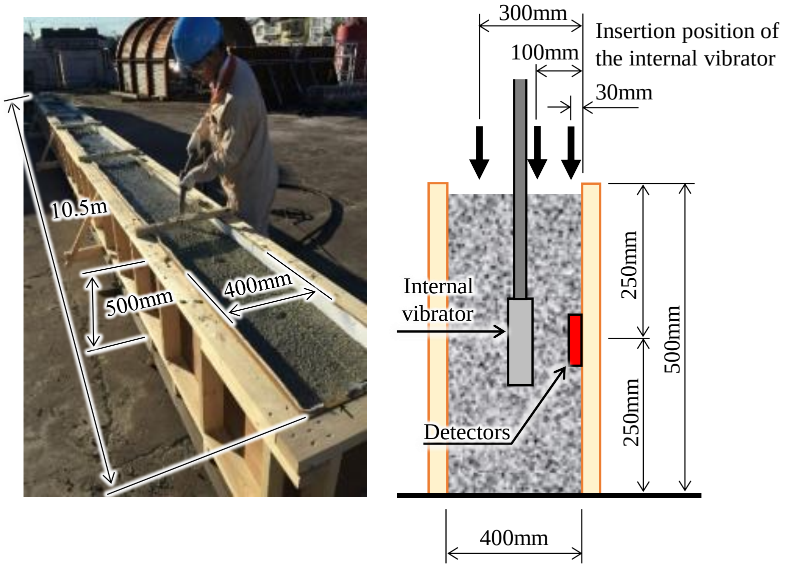


Figure 18. Experiment with the wooden mock-up

Table 3 Mixture proportions.

No.	W/C ratio by wt.%	s/a ratio by wt.%	S/C ratio by wt.	Unit weight, kg/m^3			
				Water	Cement	Fine agg.	Coarse agg.
C4-1	56	47.4	2.7	172	308	838	949

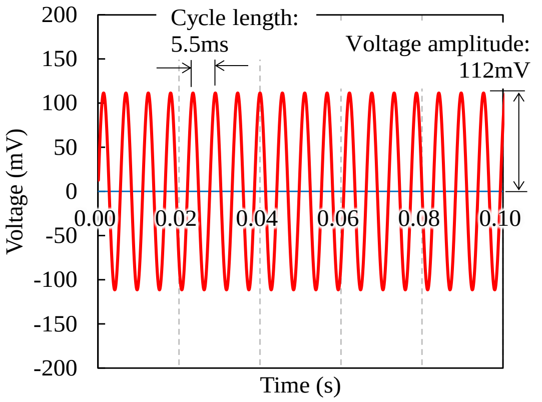


Figure 19. Wave profile output by the compaction detector at 30 mm intervals

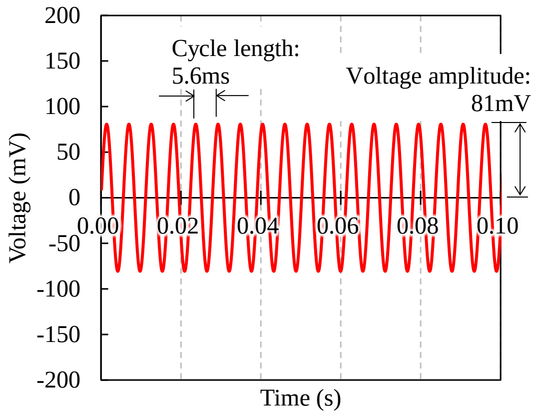


Figure 20. Wave profile output by the compaction detector at 100 mm intervals

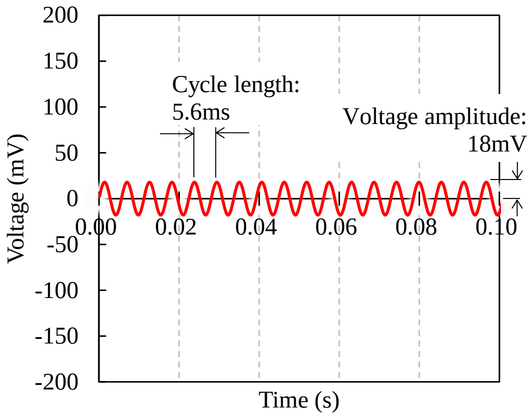


Figure 21. Wave profile output by the compaction detector at 300 mm intervals

Figures 19, 20, and 21 show the wave profiles output by the detector for compaction at the 30 mm, 100 mm, and 300 mm intervals between the detector and the internal vibrator, respectively. The voltage frequency measured at all positions was approximately 180 Hz, equivalent to a cycle length of 5.5–5.6 ms. The results show that the intervals did not affect the voltage frequency. However, when compared with the output frequency of 200 Hz, the measured frequencies had decreased. The reason for this decline was the resistance of the fresh concrete to the angular velocity of the vibrator, which was derived from a rotary movement generated by high-speed rotation of the small unique weight in the vibration motor. In addition, the voltage amplitude decreased in inverse proportion to the interval size. The degree of this decline may be dependent on the concrete mixture proportions. It will thus be necessary to study the compaction detector's aspect ratio and area to enable vibration detection for any mixture proportions.
In addition, some voltage frequency ranges other than that around 180 Hz were observed discretely. We concluded that these ranges were caused by the on-board motor in the internal vibrator and other electronic devices. Any voltage frequencies in which the voltage amplitudes did not change with the different intervals and that were higher than the output frequencies of the internal vibrator could be eliminated as electromagnetic noise. We are currently applying an improved system containing a noise

filter program and can therefore conclude that the developed sensor can selectively capture the vibrations from the internal vibrator when propagating in fresh concrete.

5. Conclusions

The results from our fundamental experiments proved that the proposed sensor system, which uses multiple detectors on both sides of a long, thin sheet, is capable of detecting both filling and compaction of fresh concrete. The findings from this study with regard to the electrical characteristics are as follows. The electrical impedances of fresh concrete, fresh mortar and bleeding water were grouped without overlaps when concrete and mortar with generally applied mixture proportions were used. Furthermore, the electrical impedances of concrete and mortar have a strong relationship with the effective cement paste volume, which is obtained by subtracting the cement paste volume absorbed around aggregates from the total cement paste volume. Based on this relationship, it is possible to predict the degree of material segregation in fresh concrete. The findings with regard to vibrational characteristics are that the distance from an internal vibrator does not affect the voltage frequency, although the voltage amplitude does decrease with distance. This study shows that the knowledge of these electrical and vibrational characteristics can be used to stimulate innovation in quality control for construction of concrete structures.

Acknowledgment

We thank David MacDonald, MSc, from Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

References

Fujikura, Y. (2012) "Study on Evaluation of Water Content from Concrete Placing to Hardening and Quality Control during Concrete Work based on Change in Capacitance (in Japanese)", *Proceeding of the Japan Concrete Institute*, 34(1): 1336-1341

Hirata, T. and Sogo, S. (1996) "Study on Detection of Concrete Filling with Voltage Application Method (in Japanese)", *Proceeding of the Japan Concrete Institute*, 18(1): 69-74

Iwasaki, N. and Sakamoto, N. (1989) "Propagation Characteristics of Vibration in Fresh Concrete from Internal Vibrator (in Japanese)", *Journal of JSCE*, 402(10): 87-96

Kaneko, M., Yasuda, M., Sueoka, E. and Sakai, T. (2009) "Development of Concrete Filling Detector with Compaction Detector (in Japanese)", *Proceeding of the Japan Concrete Institute*, 31(1): 2077-2082

Madhavi, T. Ch. and Annamalai, S. (2016) "Electrical Conductivity of Concrete", *ARPN Journal of Engineering and Applied Sciences*, 11(9): 5979-5982

Ota, M. and Iyoda, T (2015) "Study on Hardening Concrete by Electrical Resistance Value (in Japanese)", *The 5th Symposium on Non-destructive Inspection for Concrete Structure*, 5: 119-122

Sakai, G., Yurugi, M., Sakata, N. and Iwaki, M. (1995) "Application of Highly Fluidized Concrete Considering Quality Assurance of Structures (in Japanese)", *Proceeding of the Japan Concrete Institute*, 17(1): 233-238