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Development of smart sensor formwork system toward high quality concrete structures

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ABSTRACT: Formwork removal from concrete has been conducted based on either the prescriptive requirement for ages of concrete or the performance requirement for strength development of concrete tested using in-situ cured specimen. Quality of concrete obtained with the former depends highly on environmental conditions and constituent material characters, and the latter generates concrete waste. To solve these problems, the smart sensor formwork system was developed, which can monitor the temperature and electrostatic capacity of concrete, and the installed angle of form. The concrete surface temperature history permits tracking, on site and in real time, of strength development of concrete. Plotting the strength data on the form layout drawing provides a visual display of the strength distribution which helps immediate assessment of locations lacking strength or reaching necessary strength. In these ways, the proposed smart sensor formwork system enables a new direction toward higher-level and more sophisticated quality control of concrete structures.

1 INTRODUCTION

An increasingly high level of quality control has recently been required of concrete during the form retention period after placing, as it is strongly related to shortening of the construction time and the quality assurance of the concrete structure. The authors thus developed a comprehensive quality control system for concrete, or the “smart sensor formwork (SSK) system.” This is a system whereby quality control of concrete during curing is carried out through surface strength estimation and visualization using embedded software based on such data as the state of formwork retention, number of times of the use of forms, and temperature history of concrete surfaces, which are collected through a wireless network. To transmit such information without burdening workers, the authors devised small integrated circuits having sensors by successfully combining small sensors and chips already available on the mature market and dedicated sensors originally developed by the authors, which are installed on resin or steel formwork.

There have been techniques for the quality control of concrete utilizing electronic information, such as embedding RFID by Sugiyama (2009). Instead of mixing such small chips as IC tags in concrete, the present system incorporates microcomputer modules in resin formwork for concrete and installs applications having various features on these microcomputers. When concrete is placed and comes into contact with the resin forms, the applications incorporated in the forms are activated, like those installed in smartphones, and begin the process of logging the date, measuring the temperature, and estimating the strength of concrete surfaces. As shown in Figure 1, a handy reading computer (smart reader) communicates with each form through the wireless network, providing appropriate information for judging the right time of form removal. The SSK system is a platform that enables comprehensive quality control to maximize the efficiency of concreting work, which is under pressure of further cost reduction and quality enhancement. This system has already been introduced to various actual concreting projects, including a trial in a dam project.

2 OUTLINE OF SSK SYSTEM

Table 1 gives a summary of the features and specifications of the SSK system. Table 2 compares the performances of SSK with those of plywood formwork. The SSK system has a number of advantages including a short construction time. In view of the eventual price per square meter to be equivalent to conventional wooden formwork on a total cost basis, the SSK system has been supplied for rent as a package incorporating resin formwork and a smart sensor system. The adoption of microcomputer-controlled multifunctional sensors enabled automatic traceability management of resin formwork. This made it possible to supply the system on a rental basis, which significantly increased the cost advantage of using this system for users. The usability of this system has currently been investigated at various concreting sites.

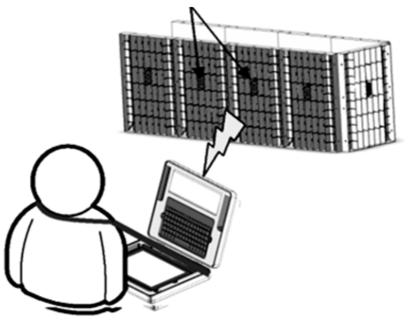


Figure 1. Smart sensor formwork system.

Table 1. Functions and specifications of smart sensor formwork system

Functions and specifications	Note
Recording the time of concrete placement	Concrete placement is detected by a capacitance sensor and its date and time are recorded.
Measuring the ambient and concrete surface temperature	Ambient air temperature around a formwork and temperature of concrete surface contacting with a form are measured and recorded by temperature sensors.
Recording the time of formwork removal	Formwork installation and removal are detected by an acceleration sensor and their date and time are recorded.
Wireless communication	Maximum range of radio communication is 15 to 20 m.
Battery lifetime	Battery can work for 7 to 10 years.
Operating temperature range	Smart sensor can work within a range of -10 to 60 °C.

Table 2. Comparison between smart sensor formwork system and traditional plywood formwork system

Item	SSK system using	Plywood formwork system
Mass of form (600x1800 mm)	10 kg	12 kg
Light transmission	Permeable, Easy to work	Impermeable
Dimensional stability during operation	Stable	Unstable, Subject to deformation and breakage
Construction speed	Faster than plywood system	-
Maximum number of reuse	50 to 100 times	5 times
Recyclability	Material recycle	Thermal recycle
CO_2 emission per utilization	9.6 kg/form	12.6 kg/form
Cost	Reducible	-

3 STRENGTH ESTIMATION BY EFFECTIVE AGE

The SSK system allows automation of the decision of the time for form removal by estimating the surface strength of concrete. In concreting work, strength estimation of concrete is a critical factor that strongly affects the construction period and quality. It should therefore be most precise and helpful among other features of this system. The degree of cement hydration is strongly linked to strength estimation. Due to being a chemical reaction, its rate depends on temperature. Since a higher temperature leads to a higher reaction rate, for instance, concretes cured in different temperature ranges for a certain period show different strength gains. A concrete cured at a lower temperature has to be cured for a longer period than one cured at a higher temperature to achieve the same strength. In this manner, cumulative temperature has been used for strength estimation and quality control based on the concept that the relationship between the product of temperature and time and the compressive strength is uniquely determined. In fact, however, the quantitative relationship between the rate and temperature of chemical reaction can be organized by Arrhenius plots based on the Arrhenius law, and this reaction law agrees with the concept of chemical potential in thermodynamics. For these reasons, the method of organizing data based on the Arrhenius law has recently been used more generally than cumulative temperature in many fields worldwide. An effective age in the field of concrete is defined as an age incorporating the temperature dependence of reaction rate by using the Arrhenius reaction law. It can be expressed as the equation given below by assuming the reaction rate when the concrete is 20°C to be the standard reaction rate and the activation energy to be 33kJ/mol based on fib Task Group 8.2 (2008) and using absolute temperatures.

$$t_e = \sum_{i=1}^{n} \Delta t_i \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)/t_0}\right] \quad (1)$$

$$f_c\left(t_e\right) = \exp\left\{ s\left[1 - \left(\frac{28}{(t_e - s_f)/T_0}\right)^{1/2}\right]\right\} f_{c28} \quad (2)$$

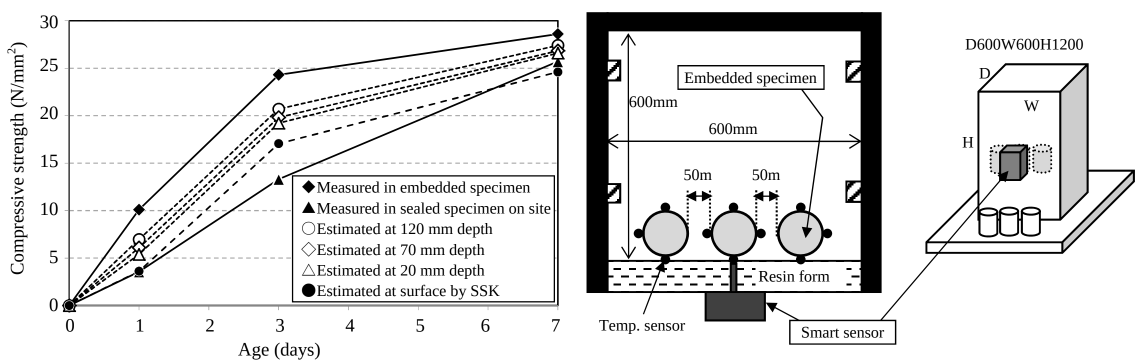
where $f_c(t_e)$ = compressive strength of concrete (N/mm^2)
t_e = effective age of concrete (days)
t_0 = 1 (day)

T_0 = 1 (°C)
fc_{28} = 28-day compressive strength of concrete (N/mm^2)
s = constant for cement type
s_f = correction term for the origin of hardening (days)

It is clear that cumulative temperature ('maturity') is also uniquely related to compressive strength, as it is proportional to the integrated inverse of the natural logarithm of reaction rate when the equation is deformed based on the Arrhenius law. Nevertheless, effective age organized through the Arrhenius law has been generalized to a greater extent so that the same equation would be applicable to most concrete by simply changing the coefficient for each characteristic of materials, such as types of cement and supplementary cementitious materials. Also, the factors are more flexible, being easier to give some sense in terms of chemical reaction, such as retarding or accelerating action. Moreover, the meaning of the values is easy to understand instinctively, as they correspond to the number of days cured at 20°C. Effective age is widely used in research papers dealing with the mechanical properties of concrete domestically and worldwide. The International Federation for Structural Concrete (formerly abbreviated as "CEB-FIP," currently "fib") adopts effective age for its strength estimation equation for the quality control of concrete. In 2002, it was also adopted by the Japan Society of Civil Engineers in the "Standard Specifications for Concrete Structures, Structural Performance Verification". Though effective age may not yet be generally used at jobsites for civil structures in Japan, its use is a global trend.

The applications for the SSK system are applicable to quality control by either of effective age and maturity, but strength estimation by effective age is the standard setting, because it is widely applicable to various types of concrete.

Assuming a concrete structure, Figure 2 compares the compressive strength of specimens seal-cured at the jobsite, strength of specimens embedded in the concrete structure, and strength estimated based on the effective age determined by temperature measurement using the SSK system. Even if cured at the jobsite, the temperature history of specimens can widely differ from that of concrete in the actual structure depending on the effect of the size of the structure. The strength estimated by effective age determined from the surface temperature data of concrete measured using the SSK system is found to be closer to the strength developing near the surface of the actual structure than that of concrete specimens cured at the jobsite.



Strength development of specimens and estimations   Outline of experiment

Figure 2. Comparison in strength development between with specimens and through smart sensor.

4 "PLANAR" CONTROL OF THE ENTIRE STRUCTURE

As stated in the previous section, the SSK system allows strength estimation of the concrete surface in contact with each form based on effective age. It follows that an efficient system becomes necessary for simultaneously controlling concrete in contact with all of the dozens or hundreds of forms incorporating smart sensors at the jobsite. The SSK system provides a tablet-type computer referred to as a "smart sensor reader" that allows communication with each sensor installed in each form using a wireless network system. Users can carry it around on the jobsite to collect the information by communicating with sensors installed on each form. The smart sensor reader is capable of estimating the strength of concrete surfaces in contact with each form based on the collected temperature history, displaying the color map of the estimated concrete surface strength on the form layout prepared beforehand (Figure 3), and summarizing the maximum, minimum, and average of the obtained surface strengths into graphs (Figure 4).

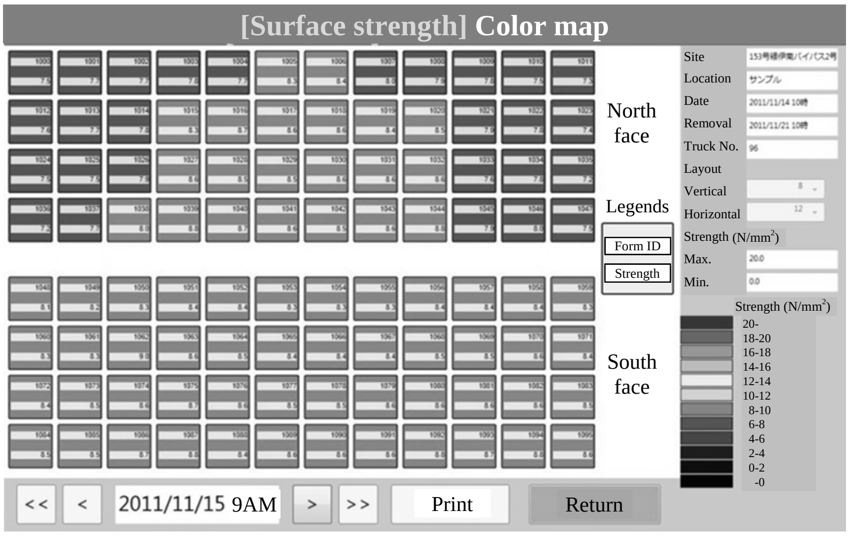


Figure 3. Color map of the estimated concrete surface strength on the form layout.

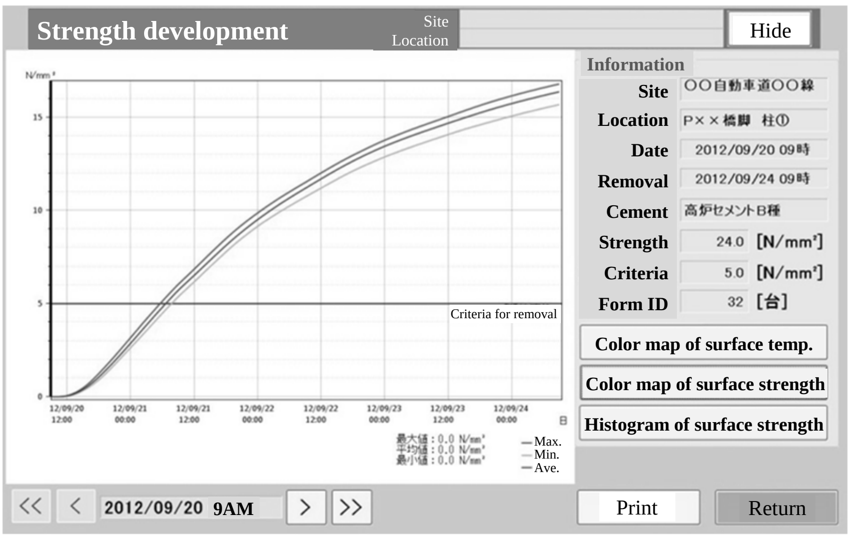


Figure 4. Maximum, minimum and average of the obtained surface strengths.

Such "planar" control has been introduced to jobsites for concrete structures that need this type of control. These include multiple retaining walls and bridges on a practical basis and a concrete dam on a trial basis, with verification being performed (Figure 4).

Generally speaking, concreting in winter is often carried out under extremely low temperature conditions. This may cause the temperature of certain portions of concrete to be far below the temperature necessary for hardening, depending on the effects of wind and solar radiation, as well as the shape of the structure. Measures should be taken to increase the temperature, such as using heating equipment, jet heaters for instance, or curing sheets having an insulating function. The SSK system outputs the ambient temperature after concrete placing, surface temperature of concrete, and estimated strength of concrete, enabling engineers to visually locate the points of low temperatures and low strengths on the visualization software.

When planar temperature measurement is to be conducted for the purpose of quality control, the number of thermocouples installed in a plane has generally been limited due to the large amount of labor required for installation. In this case, thermocouples should be placed along the edges, in the shaded portions, and other parts requiring sufficient care, but the temperature, which by its very nature depends on the surrounding environment, could be low at unexpected locations. Also, as to equipment or treatment to support heating or insulation, it is difficult even to check their effects in many cases when formwork is retained or when there is little space available, being close to scaffolding or other equipment. In this regard, the SSK system provides real-time data on measured outdoor air temperature and concrete surface temperature, as well as estimated concrete surface strength even at inaccessible locations at a cost nearly as low as conventional methods using plywood formwork. Engineers can thus readily confirm the points of low temperatures and whether or not the insulating measures are actually working.

Figure 3, for instance, clearly shows that the strength development tends to be slow near the corners of the form facing north due to the low ambient temperature. In fact, important consideration has already begun, such as verification of the effect of heating by jet heaters, for improvement in quality control at jobsites to which the SSK system was applied.

When investigating precise temperature distribution on the surfaces of concrete placed in conventional wooden formwork for the purpose of technical verification and research, substantial time and personnel have been necessary for the installation and wiring of a large number of thermocouples. Moreover, conventional methods involve undeniably unstable factors, such as the risk of thermocouple disconnection and the limitations in the temperature range of data loggers to which thermocouples were connected (temperatures outside the range of 0-50°C often cause abnormal reading). In contrast, the SSK system eliminates such concerns, as data are collected from sensors installed in formwork through a wireless network, while the operating temperature of the sensors ranges from -10°C to 80°C, with the limits being wider than the combination of thermocouples and data loggers. Therefore, measurements of greater stability and efficiency can be performed.

5 CONCLUSIONS

The smart sensor formwork (SSK) system has begun to be used at many construction sites. We were told that the reason that contractors are selecting this system is that in most cases the possibility of a drastic increase in the efficiency of concreting in unstable environments is expected. Concreting of a structure having a complicated shape in winter particularly requires meticulous curing, as it involves crucial factors to be considered for quality control, such as solar radiation, wind direction, and wind speed. Conventionally, however, only jet heaters, insulation sheets, etc., have been applied by guesswork as stated above.

This winter, the authors are having the insulation-type SSK system applied on a trial basis. This is a new SSK system including insulation forms of original specifications. Due to being insulated, this formwork is capable of fully utilizing the hydration heat of concrete for heat retention, contributing to the stabilization of early-age curing. Since the temperature sensors installed on the forms can be used for evaluating the insulating effect as they are, the new system provides not only adiabatic curing but also real-time monitoring and evaluation of the degree of insulation curing, which can also be checked using automatically recorded data.

The SSK system is planned to flexibly add new features and evolve to meet the needs of the field as a key platform for quality control in concreting. The authors intend to continue research to elaborate this system for higher performance and quality of concrete structures so as to enable it to contribute to further streamlining and upgrading of quality control.

6 REFERENCES

Sugiyama. H, Ohkubo, T, and Nakajima, S. 2009. Communication performance of IC-tags installed inside concrete. AIJ Journal of Technology and Design, AIJ, 15, 29: 9-14

fib Task Group 8.2. 2008. Constitutive modeling of high strength/high performance concrete. fib, 42: 103