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Smartphone-Based Data Collection System for Repetitive Concrete Temperature Monitoring in High-Rise Building Construction

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Abstract: The systematic collection and management of on-site information in high-rise building construction are important factors in construction management. Recently, wireless sensor network (WSN) technology has been utilized to manage the various tasks involved in high-rise construction efficiently and in a timely manner. However, because of the repeated installation of sensors and repeaters along with the construction progress, the existing WSN technology is ineffective when applied to the temperature management of concrete in structural work. Here, we propose a new data collection method in which a worker uses a smartphone to repeatedly monitor concrete temperature. In field implementation, the proposed system enables concrete temperature management without a transmission gap for monitoring in 60-min intervals with smartphones provided to 20% of the structural workers. Next, a case study was performed on a high-rise building construction site to analyze the effectiveness of the proposed system in terms of cost savings by avoiding schedule delay. The results of the case study show that the proposed system can reduce the additional work costs resulting from delays in concrete curing and save up to $18,907 in labor costs. In addition, this system can reduce the temperature management time of the quality manager and enable more efficient management. It is also expected that this system will contribute to on-site waste management by reducing the number of embedded sensors.

Keywords: data collection system; worker's smartphone; concrete temperature monitoring; high-rise building construction

1. Introduction

Accurate and timely management of on-site information in high-rise building construction is a crucial element for the success of a project [1]. In high-rise construction, a large amount of real-time information is available because various tasks are performed simultaneously [2]. If on-site information for timely management is missing or delayed in transfer, subsequent processes may in turn be delayed or rework may be required [3]. As a result, increasing efforts are being made to collect information in real time for on-time action in high-rise construction.

Various wireless sensor networks (WSNs) have been applied for timely and efficient construction management in high-rise building sites. WSNs collect real-time information using the sensors installed on the site and transfer the information to the manager's device wirelessly through a router. It is possible to reduce the information collection task of the manager and to share accurate information by collecting real-time information automatically. In the construction field, WSNs are mainly applied to progress monitoring, material tracking, and safety monitoring, in which real-time information is required [4].

However, existing WSN-based data acquisition methods are not efficient for use in repetitive tasks such as concrete temperature monitoring in high-rise building construction. In structural work, the temperature of concrete is an important element to estimate the strength of concrete in the corresponding time [5]. Because the construction process of the next floor can begin when the strength of concrete is met, managing the temperature for strength development is very important in the high-rise construction schedule, which has generally a short floor cycle [6]. Furthermore, it is important to measure the concrete temperature in real time because it varies considerably depending on the outside weather. Consequently, sensors and routers must be installed on every floor to apply a WSN to structural work. Repeated installation of hardware on every floor requires additional work cost and time and may negatively affect construction waste management due to the number of embedded sensors required [7]. In addition, obstacles such as the steel materials of formwork may lower transfer rates from sensors to routers. Maintenance of the devices installed on a site is also difficult because of the rough environment, for example, with dust at the construction site or changes in outside weather.

Data collection by workers using smartphones can be an efficient solution for repetitive concrete temperature monitoring in high-rise construction. Because people commonly use smartphones every day, data collection by workers using the ubiquitous sensors embedded in smartphones has been attempted at construction sites [8]. Smartphones can replace the sensors or routers of the existing WSNs because they have various sensors and communication environments [9]. If smartphones are used instead of routers in high-rise construction, data can be transferred without router installation on every floor and the cost of devices can be saved. In addition, because workers continuously move in the work area, data transmission failure because of obstacles can be minimized.

This study proposes a new data collection method using smartphones to improve the efficiency of repetitive data collection such as monitoring concrete temperature in high-rise frame construction. In this study, the concrete temperature monitoring systems using existing WSNs are reviewed. Then, the architecture of a new monitoring system with workers using smartphones is outlined, and major technologies are demonstrated. Next, the system is implemented through a field test on an actual high-rise building construction site. Based on the collected data, the feasibility of the system is discussed by analyzing the transfer rate. Lastly, the effectiveness of the proposed system is analyzed in terms of cost savings by preventing schedule delay through a case study. It is expected that the results of this study will enable efficient data collection and monitoring in high-rise frame construction and contribute to preventing construction delay caused by the concrete temperature and securing excellent quality.

2. Literature Review

2.1. Monitoring System for Concrete Temperature

In general, existing concrete temperature monitoring systems using WSNs consist of sensor nodes, a repeater, a router, and a server (Figure 1) [10]. Sensor nodes refer to sensors and devices with a communication function to transfer sensor data. The information measured by a sensor is transferred to a nearby repeater or router using a local area network (LAN). The repeater also transfers the information from a sensor node to a router if the transfer distance of a sensor node is long. The router transfers the information to a server using a wide area network (WAN). The LAN of existing monitoring systems uses Zigbee, Bluetooth, and radio frequency identification (RFID), while WAN performs wireless transfer to servers using wideband code division multiple access (W-CDMA). Existing monitoring systems have been applied to mass concrete with high hydration heat or cold weather concrete to monitor the concrete temperature.

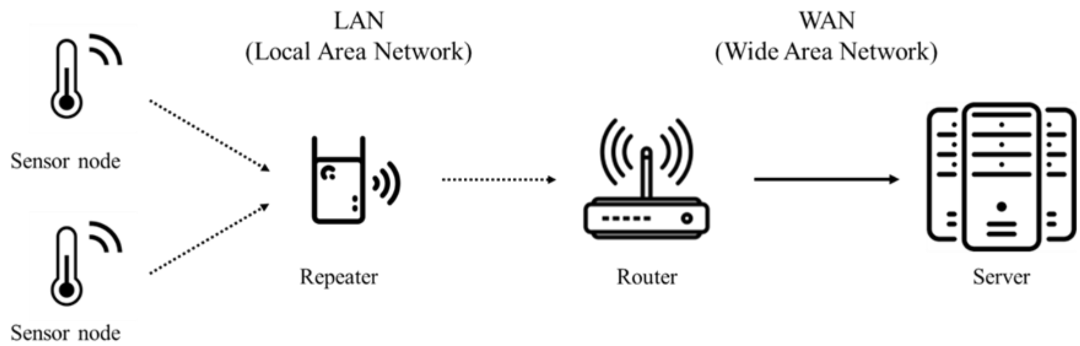

Figure 1. Existing concrete temperature monitoring process using a wireless sensor network (WSN).

Because existing concrete monitoring systems were developed to be used only during a required period, they are not suitable for repeated structural work in building construction. For repeated use, sensor nodes and routers must be continually moved to the required area. Such additional processes increase costs and construction time, and construction waste also increases because of the required number of embedded sensors. Furthermore, because formwork materials and structures may interfere with transmission, more repeaters may be required depending on the building type. Thus, when applying a WSN-based monitoring system to structural work in high-rise construction, a method capable of minimizing the reinstallation of devices and improving transfer rates is required.

Most studies on using WSNs for concrete curing temperature monitoring are targeted at mass concrete and focused on improving sensor accuracy and economic efficiency. Lee et al. [11] developed a ubiquitous sensor network (USN)-based mass concrete curing management system and applied it to foundation concrete. Embedded sensors and a radio frequency (RF) modem were used, and the RF modem was connected to a server by cable. Because the system was installed in an open space for mass concrete, obstacles against transmission and system reuse were not considered. Norris et al. [12] proposed a system capable of measuring the concrete temperature and humidity using nanotechnology/microelectromechanical devices. Accuracy was improved compared with existing temperature sensors, but wireless communication was not considered because data were transferred to a server by cable. Chang and Hung [13] suggested a new temperature measurement technology considering a large-scale construction site environment. They studied the communication distance in an environment with external obstacles using an RF integrated circuit and temperature/humidity sensors. However, their experiment used fixed obstacles in an open area and thus had limits for application in a site environment where actual obstacles change frequently. Lee and Park [14] developed a reusable sensor node that can be attached to formwork. The node is reusable because the temperature sensor is embedded in concrete and the node can be separated from the formwork. However, in this case, cost and time increase because of the need to embed probe-type sensors and install sensor nodes on every floor. Barroca et al. [5] developed a durable and economical system for temperature and humidity monitoring using WSN. The temperature–humidity sensor embedded in concrete was connected to a communication module and monitored through an external device. However, reuse of the sensor was difficult because it was embedded and LAN has limited transfer distance. Kim et al. [15] proposed a new temperature measurement method using the surface acoustic wave. Liu et al. [16] improved the transfer distance of the embedded module using the embedded RFID sensor tag and outlined an economical system. However, again, those two studies had limits with respect to reusability because embedded sensor nodes were used. Cabezas et al. (2018) [17] developed and field-tested a concrete curing monitoring system using a compact embedded wireless sensor. That study focuses on determining how to withstand the harsh environments where embedded sensor nodes are installed and how to save energy in sensor node communications. Jianshu et al. [18] proposed a framework of cracking control for a mass concrete structure by taking advantage of Distributed Temperature Sensing (DTS) system and showed higher efficiency in temperature data acquisition than conventional electric converters. Angat et al. [19] developed an integrated system by analyzing combined measurements of RFID and optical fibers. That study focused on the measurement method for improving the measurement performance of a concrete curing monitoring.

Previous studies conducted experiments in laboratory environments and thus focused on sensor accuracy, economic efficiency, and transfer rate of information. Thus, research on a new data collection method is required for operation inside building construction that requires many repeated installations and has many obstacles in the structural construction of a high-rise building.

2.2. Data Collection Systems Using Smartphones

To address the drawbacks involved in sensor installation and maintenance of existing USN technology at construction sites, data collection methods using smartphones with built-in sensors have been utilized [5]. Because smartphones have various sensors and communication modules capable of accessing both WAN and LAN and are easy to carry, they have replaced most devices previously used at construction sites.

Previous studies on smartphones focused on the manager's smartphone and improved the efficiency of on-site information management. Dong et al. [20] improved the information management efficiency between the site and the office using mobile phones for construction defect management. Lee and Kim [21] suggested measures to streamline the lifted material management process using smartphones. Kim et al. [1] developed an on-site management system capable of performing the functions of site monitoring, task management, and real-time information sharing using mobile computing technology. Park et al. [22] proposed proactive construction defect management using mobile devices and augmented reality.

As smartphone penetration continuously increases [23], studies that use workers' smartphones have been conducted. Cobili et al. [24] suggested a mobile system that can confirm the activities and on-site presence of workers. Ahn et al. [25] suggested a system for checking the attendance of workers at a construction company using the smartphone's Global Positioning System(GPS). Dominics et al. [26] analyzed the usability of workers' smartphones to identify their work position information. Dzeng et al. [27] presented an algorithm that can detect falls or signs of falls of workers using the acceleration sensor of workers' smartphones. Akhavian et al. [28] suggested an application capable of recognizing the activities of workers for each process by classifying the activities for each work process and utilizing the smartphone's gyroscope and acceleration sensor. Yan et al. [29] developed a real-time motion warning system to help prevent injuries that can recognize the incorrect movements of workers using smartphones attached to helmets and vests. Zhang et al. [30] proposed a decision tree algorithm that can more accurately recognize a worker's activity by using the accelerometers and gyroscope sensors of a smartphone. Zhang et al. [31] explored potential applications of the worker's smartphone as a data acquisition tool to detect near-miss falls on the basis of an artificial neural network.

Thus, existing studies on data acquisition systems using smartphones at construction sites have evolved from a focus on real-time site information using the manager's smartphone to those using workers' smartphones. This trend means that workers' smartphones can be expanded to individual monitoring systems that include sensors and network functions, thereby measuring a variety of on-site data. However, previous studies only covered information that could be measured by the built-in sensor of a worker's smartphone. To better manage on-site information, the worker's smartphone can be used as a router for transmitting information. In this way, the smartphone can be utilized as individual communication nodes that construct a network on site. Here, we present a new method to monitor concrete temperature information by using workers' smartphones as a router.

Although Lim et al. [32] conducted a preliminary analysis of a new data acquisition method using smartphones, they only analyzed the economic aspect of the concept model for the proposed method. The present study proposes the specific method and technical details of a fully developed system and verifies its practical aspects through a field experiment.

3. A Smartphone-Based Data Collection System (S-DCS)

3.1. Research Method

The research method of this study is shown in Figure 2. First, the framework of S-DCS was drawn up, and then each elementary technology was developed to produce a prototype. Next, to test the feasibility of the S-DCS, a field test was performed to analyze the data rate for each variable. Lastly, to verify the effectiveness of S-DCS, the cost effectiveness of this system was analyzed through a case study of a high-rise construction site.

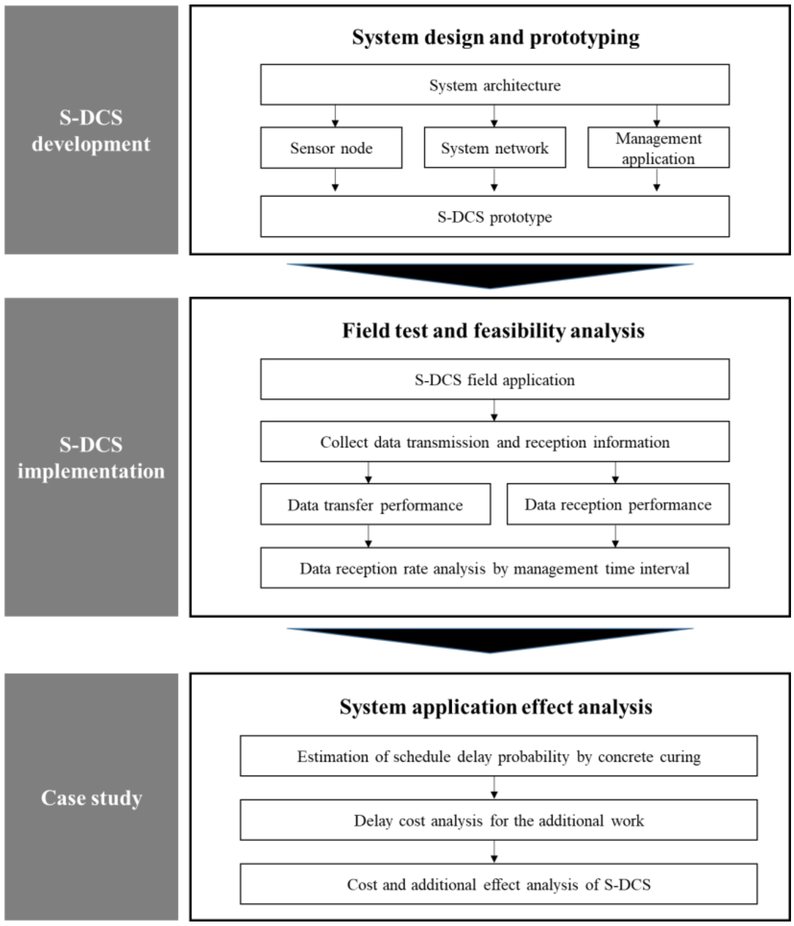

Figure 2. Research process. S-DCS: Smartphone-Based Data Collection System.

In the system development part, S-DCS was designed based on the requirements for repetitive concrete temperature monitoring by dividing by sensor node, system network, and management application. Next, we prototyped the sensor node and application for the field test of the system.

In the S-DCS implementation part, feasibility was tested by applying S-DCS to a 42-story high-rise building construction. The sensor node was installed in the slab formwork, and the workers were given a smartphone to measure the concrete temperature in the construction of one floor. During the construction period, a video was taken to identify the location of the smartphone held by the worker at the time the data were received. The time and number of times sent from the sensor node were checked for the log data of each sensor node, and the received time and number of smartphones were checked through the application of the smartphone. The data transfer performance and data reception performance of smartphones are analyzed by the distance between the sensor node and the smartphone, transmission time of the temperature data, reception time, and number of times transmitted. In addition, based on the collected data, we analyzed the feasibility of this system through data reception rate analysis by management time interval.

In the case study part, the effectiveness of S-DCS was analyzed in a high-rise building site consisting of three buildings: 77 floors, 66 floors, and 42 floors. The probability of schedule delay because of concrete curing at the site was calculated, and the delay cost for the additional work was analyzed. In addition, cost and additional effects were analyzed when delays did not occur through monitoring using S-DCS.

3.2. System Architecture

An S-DCS is designed so that data are transferred using workers' smartphones instead of routers attached to formwork for repeated use on every floor in high-rise construction. Figure 3 shows the conceptual framework of an S-DCS. The sensor node installed in the formwork records the temperature of the curing concrete and transfers the data to the smartphone of a nearby worker through LAN at regular intervals. The worker's smartphone transfers the data to a server using W-CDMA, the data communication network of smartphones. The site manager can access the server and monitor the temperature of the structure.

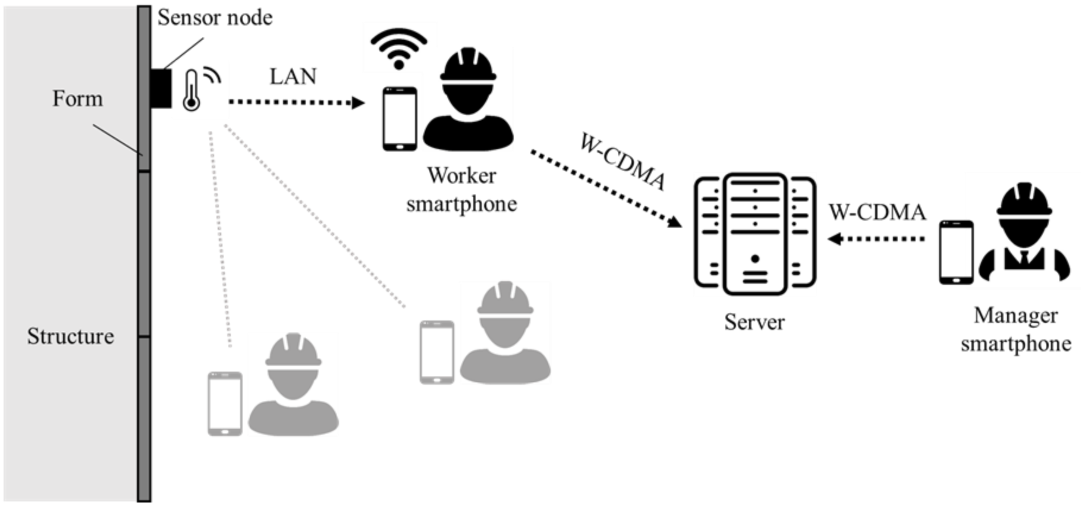

Figure 3. Architecture of an S-DCS. LAN: local area network; W-CDMA: wideband code division multiple access.

Because the sensor node of the S-DCS is attached to the formwork, repeated installation of the sensor node is not required. In addition, there is no need for additional routers or installation work because the smartphone functions as a router. Furthermore, the continuous movements of a worker's smartphone in the workspace can minimize the transfer gaps caused by obstacles such as walls and formwork materials.

3.3. Sensor Node

The sensor node in an S-DCS is attached to the bottom of the slab form and the probe thermistor penetrates the formwork and measures the temperature inside the concrete (Figure 4). Because the formwork must be installed with the sensor node attached, the sensor is attached to the formwork using four bolts. The vertical probe thermistor attached to the node penetrates the formwork so that the sensor can remain vertical during concrete pouring and can be easily separated from the formwork during disassembly. In addition, a protective cap covers the probe thermistor so that it is not in direct contact with the concrete during curing and be easily separated. Two types of probe lengths were designed to measure the temperatures of the center and the surface of the slab concrete. The slab thickness of the test building to which the sensor node prototype was to be applied was

250 mm, the probe length for the center was 120 mm, and the probe length for the surface was 20 mm. The measurement range of the temperature sensor was set between −40 °C and 110 °C, and the experiment confirmed that the error range was within ±1 °C [33].

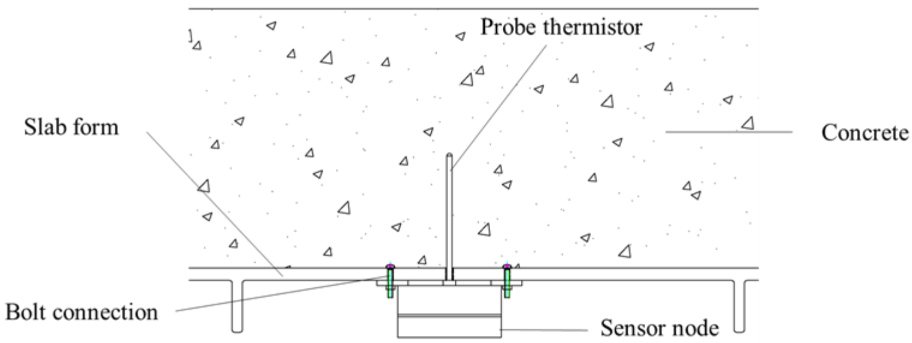

Figure 4. Sensor node installation.

The sensor node activates the temperature sensor at 5-min intervals. Because continuous temperature measurement and transfer can rapidly consume power and may cause additional work because of frequent charging, the sensor node is only activated every 5 min, and with a 700-mAh battery, it can be used for up to 30 days without charging. In addition, the sensor node has Light-Emitting Diodes (LED) that can display the status of the sensor node. The LEDs display the operation, error, and charge of the sensor node to allow the worker to identify the status at the site (Figure 5). The remaining battery capacity, activation status, and transfer error of the sensor node along with the temperature information are transferred to the server so that the manager can identify the status of each sensor node in the office.

Figure 5. Sensor node configuration. LEDs:

A cover protects the inside of the sensor node against dust and water on site. The cover and fixing pin are made of reinforced plastic to prevent corrosion caused by water entering through a hole in the formwork. In addition, a 3-mm-thick rubber cover was installed on the inside edge of the sensor node to prevent dust and water from entering, and dual rubber rings were installed where the probe thermistor is mounted on the formwork to prevent foreign matter from entering.

3.4. System Network

The local network of an S-DCS uses the Zigbee method. The local networks that can be used on smartphones include Wireless Fidelity (WiFi), Bluetooth, Zigbee, and Near-Field Communication (NFC). WiFi consumes much power and is, therefore, not suitable when continuously used because of increased maintenance work. NFC transfers data through a tag within 10 cm and is not suitable because the measurement work of the worker increases. Bluetooth and Zigbee have suitable transfer speed and power consumption for high-rise construction and are economical. Because routers move in an S-DCS, information must be simultaneously transferred to as many smartphones as possible to improve the continuity of transferred information. Zigbee can access several smartphones simultaneously, and thus, is more suitable for an S-DCS than Bluetooth, which has a limited number of simultaneous connections.

Because smartphones simultaneously and continuously move and receive data, an algorithm for missing and duplicated data was established. Figure 6a shows the data processing algorithm of the sensor node. To reduce power consumption, the sensor node selects a power supply that is activated every 5 min. When the sensor node is activated, the temperature data are collected and stored in the internal memory. Then, the sensor node checks the smartphone within the communication radius. If there is no smartphone, the sensor node is deactivated and reactivated after 5 min. If smartphones are identified, the first received smartphone is selected and the temperature data in the internal memory are transferred. When data reception confirmation is received from the smartphone, the stored data are deleted to secure memory capacity and the sensor node is deactivated again.

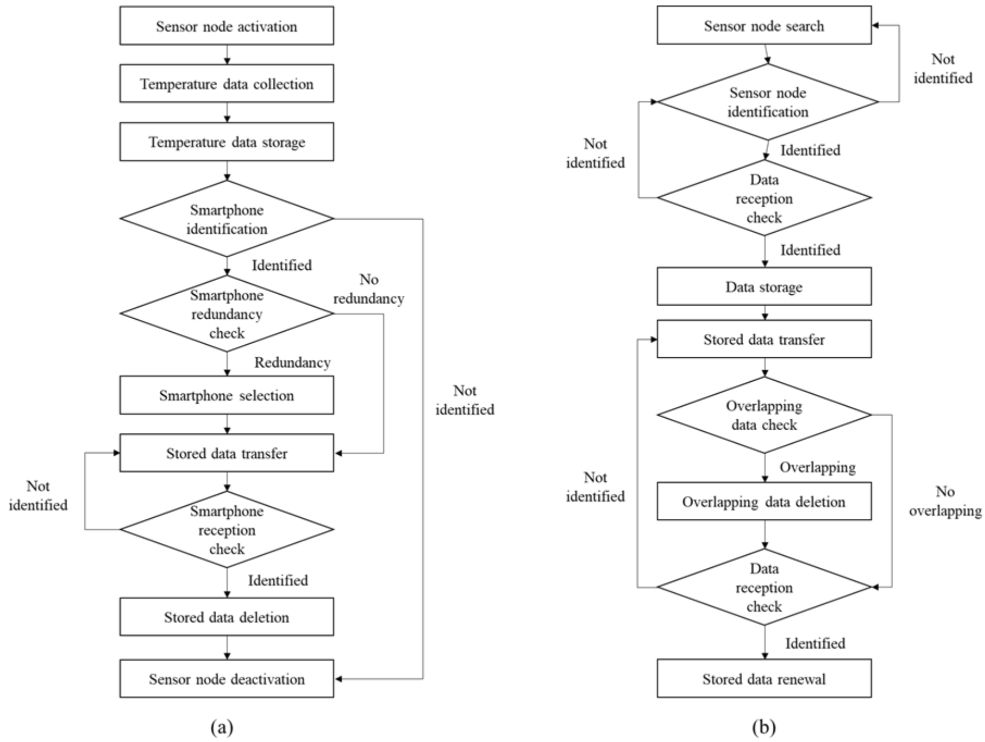

Figure 6. Data processing algorithm: (**a**) sensor node; (**b**) smartphone.

Figure 6b shows the data processing algorithm of the smartphone, and the smartphone searches for nearby sensor nodes using a Zigbee network. If a nearby sensor node is identified, data are received. If multiple sensor nodes are recognized, the data are classified and stored by each sensor node. When the data are received, the smartphone confirms the reception and stores the data. The stored data are transferred to a database through the W-CDMA network, and the transferred data are checked again for overlapping data. Any overlapping data are deleted, and the database is renewed.

3.5. Management Application

The workers' smartphones require an application to transfer and manage data. Figure 7a illustrates the interface of a function that shows the data collection status. There is a function window for data collection and stop, and a data reception and storage list is displayed in the center of the screen. The list shows the received sequence number, sensor node serial number, reception date and time, and number of data points. The monitoring application can check the device list and work area. Figure 7b shows details of the device information when the device icon is selected. The application displays the remaining battery capacity, measuring start and end time, installation location, and measured temperature graph. The sensor node information is also displayed on the floor plan when the drawing tab is selected (Figure 7c).

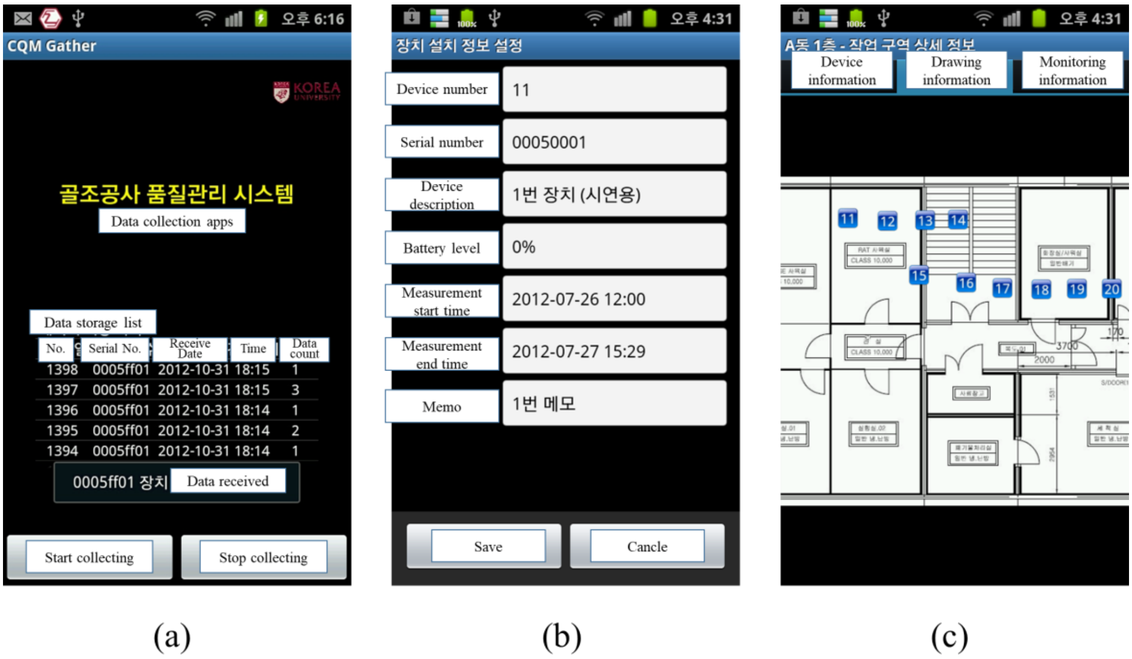

Figure 7. Application for the smartphone: (**a**) function; (**b**) node information; (**c**) floor plan.

The interface of an application for the server was designed based on the smartphone application. The floor plan of the work area can be loaded, and the sensor node and status information can be displayed at corresponding locations for management. When a sensor node is selected, the screen is converted to a monitoring screen composed of the sensor node information, and the temperature data over time are displayed (Figure 8a). For monitoring, the strength estimation graph of a structure is displayed based on the accumulated temperature. When each structure reaches the formwork-removal criterion strength, the manager is notified through the alarm window (Figure 8b).

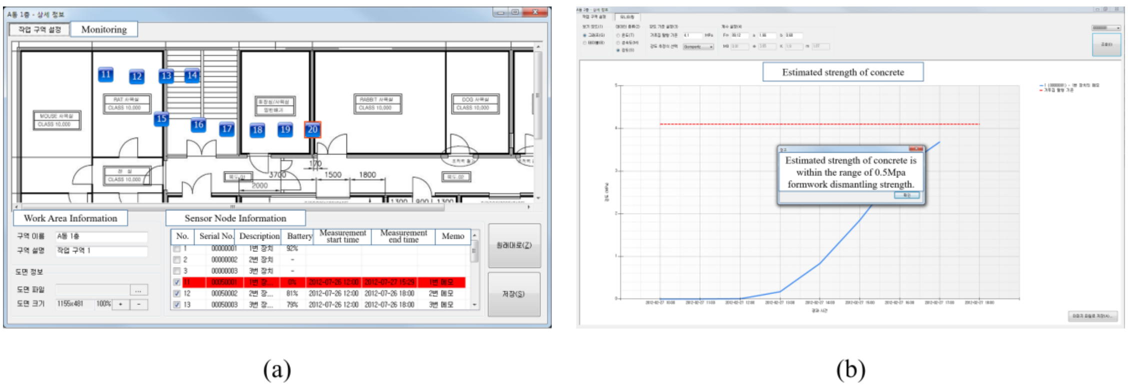

Figure 8. Application for the server: (**a**) node information; (**b**) strength estimation graph.

4. S-DCS Implementation

4.1. Outline of the Field Experiment

To test the feasibility of the S-DCS on an actual construction site, a field experiment was conducted by applying the S-DCS to structural work during construction of a tall residential building. The site was for a building with five underground floors and 42 ground floors, and it had a flat plate/slab structure. Panelized aluminum forms were used as the slab and wall formwork. One floor was divided into two work zones, and it took four working days to complete construction for each zone. The field experiment was conducted during the construction of the 31st floor of zone A, considering that the same floor construction was repeated on every floor.

Sensor nodes were installed on the slab form of a total of five areas; each area had a radius of 10 m, considering the building type and data transfer rate (Figure 9). Sensor nodes of 20 mm and 120 mm were installed side by side on a 250-mm-thick slab to examine the temperature difference according to the concrete penetration height. Two sensor nodes were supposed to be installed in each of the five areas, but one sensor node with a 20-mm probe in area E was broken while being installed; thus, a total of nine sensor nodes were installed. Because there was only one sensor node in the E area, the absolute number of transmitted and received data items may be smaller than in other areas. However, the analysis based on area compares the ratio of received data by area. Therefore, the difference in the number of data items because of the difference in the number of sensor nodes does not significantly affect this field test feasibility analysis. Thus, field tests were conducted with nine sensor nodes, and the nodes in area A were sequentially assigned a number, as shown in Figure 9.

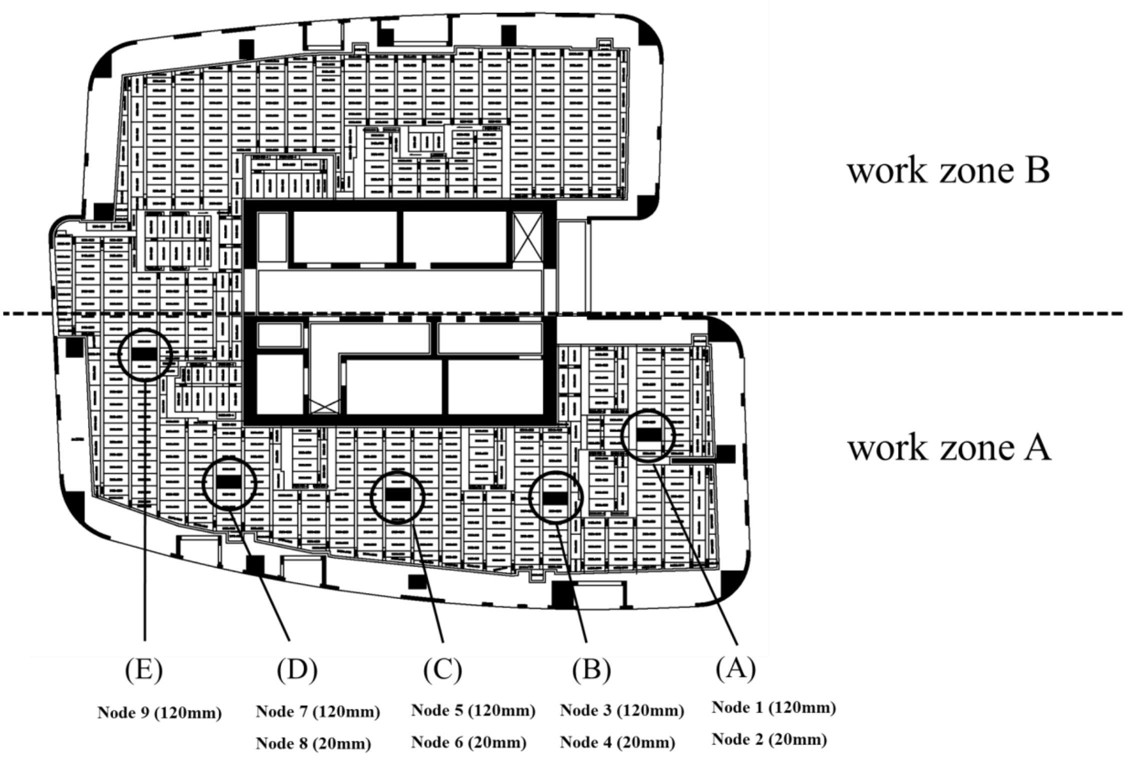

Figure 9. Sensor node installation layout.

Table 1 shows the number of workers to be provided with a smartphone during the test period. On day 1, smartphones were provided to three concrete workers and one formwork inspector in zone A and two slab formwork workers in zone B. On day 2, smartphones were provided to three workers for dismantling the wall formwork on the 30th floor of zone A and three wall rebar workers on the 31st floor. On day 3, smartphones were provided to three workers for installing the wall formwork on the

31st floor of zone A and three wall reinforcement workers. On day 4, smartphones were provided to two workers for slab form dismantling on the 30th floor of zone A, to two workers for installing wall formwork on the 31st floor, and to two workers pouring concrete on the 31st floor of zone B. The total number of workers for the four days was 135 and smartphones were provided to 24 workers (18%).

Table 1. Number of smartphones provided to workers.

Work Zone	Worker Type	Number of Smartphones Provided Per Day			
		Day 1	Day 2	Day 3	Day 4
A	Formwork worker	1	3	3	4
	Rebar worker		3	3	
	Concrete worker	3			
B	Formwork worker	2			
	Concrete worker				2
Total number of smartphones		6	6	6	6
Total number of structural workers		27	38	43	27
Provision ratio		22%	16%	14%	22%

4.2. Data Transfer Performance

Table 2 provides an overview of the temperature data transferred to the server. A total of 7538 temperature data points were transferred from nine sensor nodes to the server. The number of planned data calculated from the measurement time was 7591, which differs from the number of data points actually measured, and was caused by a delay in data transfer time and missing data. Analysis of the time intervals of the transferred data indicates that differences of a few seconds from the set time unit were observed; these accumulated and resulted in the difference from the planned number of data points, which was set as the data difference. Data that had a transferred interval of over 5 min were regarded as missing data; 46 such data points occurred because of the transfer time delay, and seven data points were missing because of transfer failures.

Table 2. Number of data transmitted per sensor node.

Node	Measuring Time (min)	Number of Data (EA)				Sensor Node Performance Ratio (%)	Data Transfer Rate (%)
		Planned Data Points	Measured Data Points	Transfer Time Delay Data Points	Transfer Failure Data Points		
node 1	4122	824	818	6	0	99.27%	100.00%
node 2	4247	849	842	6	1	99.18%	99.88%
node 3	4248	849	845	1	3	99.53%	99.65%
node 4	4249	849	843	5	1	99.29%	99.88%
node 5	4243	848	843	5	0	99.41%	100.00%
node 6	4124	824	818	6	0	99.27%	100.00%
node 7	4248	849	843	6	0	99.29%	100.00%
node 8	4246	849	843	5	1	99.29%	99.88%
node 9	4250	850	843	6	1	99.18%	99.88%
Total	37,977	7591	7538	46	7	–	–
Average	4219.67	843.44	837.56	5.11	0.78	99.30%	99.91%

The performance ratio of a sensor node can be expressed by the ratio of the number of measured data to planned data. As an index to determine the accurate frequency of when a sensor node performed data transfer, the ratio of the number of measured data to planned data excluding missing data was used. As noted, the difference between the number of planned and measured data was 46, that is, 5.11 per sensor node. The performance ratios of the sensor nodes ranged from 99.18% to 99.53%

(average, 99.30%). The results indicate that continuous monitoring is possible because the sensor nodes perform the measurement and transfer every 5 min with >99% accuracy. The performance ratio could be further improved by setting a shorter transfer time interval.

The data transfer rate between a smartphone and a server can be measured by considering the measured data and missing data. Because a sensor node sends all previous records even if transfer to a smartphone is missing, missing data occur during the transfer from a smartphone to a server. The data transfer rate is represented by the ratio of the number of measured data to that of data before the missing data are removed, excluding the data difference caused by the time difference. The data transfer rate ranged from 99.65% to 100% (average, 99.91%), indicating that monitoring is feasible almost without data transfer gaps because the server transfer rate was >99%.

4.3. Data Reception Performance of Smartphones

4.3.1. Reception Ratio by Distance

The data reception ratio of the smartphones according to various variables was analyzed to examine their performance as routers at the construction site. Only the data during working hours when the workers actually carried the smartphones were analyzed, that is, 1394 data points measured for a total of 1290 min over four days. The data reception time and transfer from sensor nodes were recorded through the log files of the smartphones, and distances to the sensor nodes were measured from the worker's location at the time of reception using recorded videos.

Table 3 summarizes the number of received data from each sensor node at a 5-m interval to identify the reception rate by distance. The distances at which most data were received were 5–10 m, accounting for 33.43% of all data. The reception rate, at 15–20 m, was the second highest at 24.46%. At shorter distances of 0–5 m, a reception rate of just 9.9% was observed. Thus, the reception ratio was higher at distances of 5–10 m and beyond than when workers were nearest the sensor node antenna. Most of the reception data were attributed to workers' smartphones received in zone B. This is likely because when area B workers approached sensor nodes when there were no workers with smartphones in zone A, reception occurred at 15–20 m. Because the number of data points by distance did not differ greatly between 5 m and 20 m, where almost 80% of data were concentrated, the results indicate that installing sensor nodes at a radius of 5–20 m can improve data reception. The maximum measurement distance was 28.34 m, indicating that measurement was possible throughout the entire work zone.

Table 3. Number of received data by distance.

Node	Number of Data Points					
	0–5 m	5–10 m	10–15 m	15–20 m	20–25 m	25–30 m
node 1	20	28	19	49	7	2
node 2	13	29	34	30	21	0
node 3	25	47	11	33	13	4
node 4	11	44	40	66	17	3
node 5	11	101	23	20	27	4
node 6	11	19	29	47	23	2
node 7	18	31	19	41	15	8
node 8	22	109	26	26	8	1
node 9	7	58	70	29	19	4
Total	138	466	271	341	150	28
Rate	9.9%	33.43%	19.44%	24.46%	10.76%	2.01%

4.3.2. Reception Ratio by Work Type

The smartphone reception rate by work date was analyzed to identify the reception rate by work type. The reception ratio of the smartphone is calculated by the ratio of the number of data points received from the smartphone and the number of those transmitted from the sensor node every 5 min. In other words, the reception ratio of the smartphone is an index that measures how much transmission gap is generated in real-time monitoring. Table 4 shows the smartphone reception rate by work date. The reception rate was lowest at 51.28% during the pouring work on the day 1 and the highest at 81.26% on day 2. The rates were 60.13% and 61.88% on days 3 and 4, respectively, giving an average of 62.85% over the four days. The reception rate of day 2 showed the largest difference of ~20% from the average due to work being stopped when it rained during the morning of day 2. As the workers were waiting without moving within the radius of the sensor nodes, the data reception rate increased. The reception rate of day 3, when the same work type was performed as that of day 2, was 60.31% and that of day 4 with a different work type was 61.88%, representing values similar to the average. These results indicate that the reception rate is affected more by the behavior characteristics of workers than by the work type.

Table 4. Smartphone reception rate by work type.

Work Date (Month/Day)	Work Type	Number of Received Data Points	Number of Transmitted Data Points	Reception Ratio (%)
day 1	Pouring concrete	221	431	51.28%
day 2	Installing wall rebar Dismantling wall form	347	427	81.26%
day 3	Installing wall rebar Dismantling and lifting wall form	537	893	60.13%
day 4	Installing wall form Dismantling slab form	289	467	61.88%
Total		1394	2218	62.85%

4.3.3. Reception Ratio by Work Area

The reception rate by work area was analyzed to identify the reception rate according to the installation area of sensor nodes. Table 5 shows the reception ratio of smartphones according to the sensor node installation area. The rate was lowest at 52.89% in (A) and highest at 75.61% in (E), as shown in Figure 9. The reception rate increased as the area moved from (A) to (E), and this was attributed to the characteristics of the work area.

Table 5. Smartphone reception rate by work area.

Construction Area		Number of Received Data Points	Number of Temperature Data Points	Reception Rate (%)
Location	Node			
(A)	nodes 1, 6	256	484	52.89%
(B)	nodes 2, 7	259	482	53.73%
(C)	nodes 3, 8	325	499	65.13%
(D)	nodes 4, 9	368	507	72.58%
(E)	node 5	186	246	75.61%
Total		1394	2218	62.85%

In zone A, the work quantities of form, rebar, and concrete are not significantly different between the left and right sides. When the work quantity is similar, the workers' movements can affect the exposure frequency of the sensor nodes. The form workers move frequently between the upper and lower floors to lift the dismantling formwork and share tools. Workers move mostly along the left path because the right path is blocked by the concrete placing boom (CPB) to go downstairs. By moving along the left path, workers are more exposed to the sensor nodes on the left side. The rebar workers move rebar from the stacked area to the work location. Given that the rebar was mostly stacked on the right side on the floor by the inside left wall, the rebar workers continuously moved to the left side of the workspace and thus the reception rate on the left side was higher.

The results show that the reception rate of smartphones—a key element for the continuity of monitoring—is affected by the distance between the sensor nodes, the behavior of the workers, and the characteristics of the work area. The distance between the sensor nodes must be within a radius of 20 m for a high reception rate, but it can be extended to 30 m under unavoidable conditions because of site characteristics. The results show that the work type does not significantly affect the reception rate if the numbers or proportions of the provided smartphones are identical. It is possible to improve the reception ratio by providing smartphones first of all to workers who move little during their work because the rate is affected by the movement frequency of workers. The reception rate is also affected by the movement path of workers according to the work area. Therefore, the reception rate of smartphones can be increased by positioning more sensor nodes at locations with low movement frequency after analyzing the movement paths of workers according to the building type, work quantity, location of stairs, and material storage location of the project.

4.4. Data Reception Rate Analysis by Management Time Interval

Because different management information requires different management time intervals, it is important to verify if data are received without data gaps within the management time for practical application of the system. In general, the maturity of concrete is measured by a time unit. Therefore, the reception rate of data was analyzed with the management time interval set to 5, 10, 30, and 60 min. Because two sensor nodes were installed in each area, the data of the two sensor nodes were combined for analysis of the reception rate.

Table 6 shows the data reception rate for each area during each time interval. For monitoring at a 5-min interval, the transfer rate was 62.85%, which was the same as the smartphone reception rate. The transfer rate increased to 80.36% for the 10-min unit and 91.67% for the 30-min unit. As the management unit time increased, data transfer gaps decreased. In particular, for the 60-min unit, the transfer rate was 100% for all areas. The maximum transfer gap occurred in area (D), where reception of the smartphones was not examined because there was no movement of the workers for 45 min.

Table 6. Data reception rate by management time interval.

Construction Area	Management Time Interval			
	5 min	**10 min**	**30 min**	**60 min**
(A)	52.89%	79.73%	91.67%	100.00%
(B)	53.73%	81.82%	96.00%	100.00%
(C)	65.13%	80.65%	90.00%	100.00%
(D)	72.58%	80.28%	91.30%	100.00%
(E)	75.61%	78.85%	87.50%	100.00%
Average	62.85%	80.36%	91.67%	100.00%

The results indicate that the S-DCS is optimal for concrete temperature monitoring at the 60-min interval with six smartphones at the site. Because the smartphones used as routers were provided to ~20% of the structural workers, it would be possible to reduce the transfer gap time and management time unit if the application were carried by more workers. Furthermore, a higher reception rate can be achieved when there is much work quantity and many workers. Considering the characteristics of high-rise sites and curing management, the S-DCS shows sufficient feasibility in terms of continuity of data transfer.

5. Case Study

5.1. Case Description

To meet the objective of S-DCS development, a high-rise building site with more than 50 floors with many repetitive floors and short construction period was selected as the case site. The case site is a high-rise building located in Busan consisting of three buildings of 77 floors, 66 floors, and 42 floors. The time for concrete curing is very short because construction proceeds at a rate of one floor every four days. Therefore, if the curing temperature is not properly controlled, the concrete strength cannot be met and the construction is delayed. To analyze the effect of the proposed system, a high-rise building under construction in winter was selected.

The time required for dismantling the slab form after pouring was 28 h. The site was constructed with a 4-day cycle for a typical floor, and heat curing and concrete temperature management were performed because of the lack of slab-curing time during the day when the average temperature was below 10 °C. During the heating curing period, floors 29–49 of building A were built, floors 27–49 of building B, and floors 18–31 of building C; concrete was poured 174 times. Table 7 shows the slab formwork area and the number of workers: 22 in building A, 19 in building B, and 21 in building C.

Table 7. Slab area and form workers by building.

	Building A	Building B	Building C
Slab area (m^2)	636	566	602
Number of workers	22	19	21

5.2. Delay Cost Analysis

In the existing curing temperature management process, the concrete may not reach the designed compressive strength because of various environmental factors. Management cannot immediately respond to variable factors that arise during the night by installing a temperature measuring device and checking the next day. Consequently, scheduling delay occurs because of insufficient management, damage to heating facilities, and sudden changes in temperature during the night. From interviews with the quality managers of three high-rise building construction projects over 50 floors, schedule delays caused by curing occurred in just 5–10% of instances of pouring concrete.

If the curing strength is not satisfactory at the time of dismantling the slab formwork, the schedule for slab formwork will be delayed, and additional work for 2 h will be required to install the slab formwork the next day to proceed as planned. The additional work cost can be estimated as the labor cost of overtime work for 2 h, and calculated by multiplying the number of slab form workers by overtime wages times the number of delays [34].

Table 8 shows the additional costs for different numbers of delays. Because the concrete is poured 174 times, delays could occur between nine and 17 times. The minimum cost of delays (9× in building B) is $8645 and the maximum (17× times in building A) is $18,907.

Table 8. Additional work costs based on the number of delays.

Number of Delays	Additional Work Costs ($)		
	Building A	Building B	Building C
9	10,010	8645	9555
10	11,122	9605	10,616
11	12,234	10,566	11,678
12	13,346	11,526	12,740
13	14,459	12,487	13,801
14	15,571	13,447	14,863
15	16,683	14,408	15,925
16	17,795	15,369	16,986
17	18,907	16,329	18,048

The S-DCS can prevent delays through immediate response by monitoring in real time the strength degradation of the concrete due to various environmental factors. Applying the S-DCS to our case site will save additional work costs of $8645 to $18,907. In addition to cost-effectiveness, real-time management also helps quality managers to reduce the time needed to install devices and manage concrete temperature, ensuring that quality managers use their time more efficiently. The number of temperature sensors embedded in concrete for temperature management can also be reduced, contributing significantly to waste reduction in the field.

6. Conclusions

In this study, a new data acquisition system was proposed for concrete temperature monitoring in high-rise construction. A network system suitable for repeated processes in high-rise construction was designed using smartphones provided to workers. The feasibility of the S-DCS was verified by applying the proposed system to a high-rise construction site. The results showed that the S-DCS can be used to monitor the 60-min management time unit without data gaps regardless of the movements of workers/smartphones.

Our study outlines the practical application of a smartphone-based data acquisition method and the variables to be considered according to the construction site. To perform real-time monitoring without transmission gaps when using this method, the following aspects should be considered. (1) If the distance of the sensor nodes exceeds 20 m, the reception ratio is lower. (2) Because the reception ratio is influenced by the behavioral characteristics of workers, it is possible to increase the reception ratio by equipping with smartphones the workers who remain for a long time in a specific area, which is the case with, for example, rebar workers. (3) It is possible to increase the reception ratio by installing more nodes in an area where there are few moving paths of workers, by considering the layout plan of, for example, material storage, the location of stairs, and floor shape. (4) The S-DCS can be practically applied in 60-min units without transmission gaps in management, and equipping >20% of structural workers with smartphones can shorten the management time interval.

The proposed system can prevent schedule delays resulting from improper concrete curing, and utilize managers' time more efficiently by omitting inconvenient tasks in the monitoring process. This system can also improve the sustainability of the construction field by avoiding material waste through the reuse of sensors and improving the structure quality through concrete monitoring. The proposed method can be applied to other data collection tasks in repetitive high-rise building construction.

The proposed system can also be extended to the monitoring of various structures through data collection methods using smartphones. For example, Chiara Bedon [35] used micro-electromechanical systems sensors to measure the information of the structure of a glass suspension footbridge and to perform diagnostic analysis. If an information collection method using smartphones is applied to the glass suspension footbridge, it is possible to efficiently monitor the information such as temperature, humidity, and vibration through the smartphone of the maintenance manager or safety manager, and the structural safety can be predicted by accumulating data. In addition, it is possible to practically apply the data collection method of this study to various structural health monitoring systems using wireless sensors.

Additional research is required on a more efficient network construction method for non-working hours when workers are not present.

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