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PERFORMANCE OF A WIRELESS SENSOR ADOPTED IN MONITORING OF CONCRETE STRENGTH

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ABSTRACT: In connection with the global trends of increasing requirements for efficiency and environmental friendliness of production, to create the safest possible conditions, innovative technologies are more intensively developed and applied. Today, an urgent issue is the improvement of systems for monitoring the construction of buildings and structures. The study presents an embedded sensor for non-destructive wireless control of reinforced concrete structures by the Maturity method, which allows monitoring data on the current concrete strength gain and internal temperature using special software. The features of the device, consisting of three main components: temperature gauges, a data collection station, and server software are disclosed. Experimental studies on debugging the sensor operation are presented. The test results presented in the work confirm the characteristics and functionality of the sensor. Thus, the strength values of concrete samples obtained by embedded sensors showed a greater convergence ($R^2 = 0.9357$) with fundamental compressive strength values, compared to those obtained by the Shock-pulse method ($R^2 = 0.8965$). Application of the proposed solution may significantly optimize the concrete formwork removal cycles speeding up the pace of construction, saving man-hours and other resources, including finances.

Keywords: Embedded sensor, Curing temperature, Non-destructive testing, Maturity index, Arduino microcontroller, Concrete strength

1. INTRODUCTION

Determining the real properties of concrete and their change over time solves many important issues associated with the design of reliable, durable, and cost-effective buildings and structures [1]. Monitoring the concrete curing temperature allows for timely control and regulates its strength gain process [2]. To date, there are two main ways of controlling the strength of concrete: non-destructive and destructive [3]. Recent decades witnessed an increasing popularity of alternative nondestructive testing methods with the use of embedded sensors [4]. Such sensors are mainly manufactured by western companies and the most recognized among them are Transtec Group (USA) producing a COMMAND Center system [5]; Giatec (Canada) produces a SmartRock maturity meter [6]; Hilti (UK) producing an HCS TH1 concrete sensor [7].

Their main advantage is that, unlike wired systems, they are not subject to potential damage at the construction site after pouring. The data is held securely on the sensor inside the concrete and can be downloaded with confidence at any time. In addition, installation and data collection are relatively easier and faster because there are no wires to pull out of the concrete [8].

Temperature-strength control of concrete using wireless monitoring sensors (WMS) includes the main processes: laboratory, field, and resultant. Laboratory tests result in obtaining isotherms of strength gain for a certain type of mixture. The field test is for obtaining data on the temperature of concrete, and the resulting calculation of the concrete maturity. ASTM C1074, USA [9]; NEN 5970, Netherlands [10]; ST-NP SRO SSK-04-2013, Russia [11] are the most known normative documents, regulating the requirements for temperature-strength control. To date, upgrading the IT architecture of the embedded sensor and the application of a unified approach to temperature and strength control of concrete is an open issue.

2. RESEARCH SIGNIFICANCE

The strength of concrete is a key indicator of its qualities. The dynamics of strong growth over a specified period allow the characteristics to be evaluated properly. Various techniques and instruments for temperature-strength control existing today are mostly oriented to large-scale construction companies. Therefore, this study proposes a wireless embedded maturity sensor with a new IT architecture with a modified electronic circuitry. This enabled reducing the cost of the constituent components and made the sensor affordable for medium and small-scale construction organizations as well.

3. DEVELOPMENT OF WMS

The development of WMS included the development of the sensor's IT architecture, assembly, software development, and sensor testing. The main components are the temperature gauges, the data collection station (DCS), and the server application (SA). The lifecycle of the system and the interaction between the users of the wireless monitoring sensor, the data collection station, and the user of the mobile or web application from a personal computer are shown in Fig. 1.

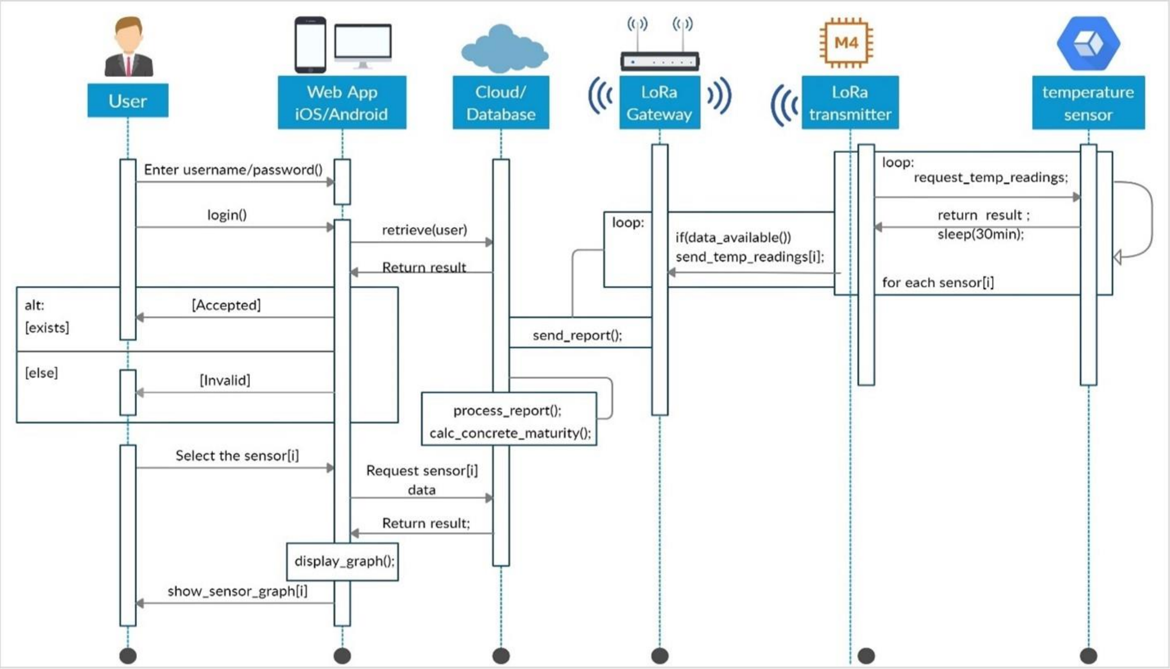


Fig. 1 Sequence diagram of the developed system

3.1 Assembly

The hardware of the temperature gauge and DCS were developed using an Arduino microcontroller. Their main metrological and technical characteristics are presented in Table 1 below.

Table 1 Metrological and technical characteristics

Name of characteristic	Value of the characteristic
Temperature measurement range, °C	- 35 to 90
Absolute error limit of temperature measurement, °C	± 1.0
Operating temperature, °C:	
temperature gauge	- 35 to 90
data collection station	10 to 40
Overall dimensions, mm, not more than:	
temperature gauge	123×43×38
data collection station	206×92×66
Weight, g, not more than:	
temperature gauge	140
data collection station	960

The sensors embedded in the body of concrete must have a robust and waterproof housing as described in [12]. Therefore, the sensor housing has a cylindrical shape, made of two-component plastic. The design and fabrication of a silicone mold for the cylindrical housing are shown in Fig. 2.


a b c d

Fig. 2 Design and fabrication of a silicone mold for a cylindrical body

To optimize the temperature gauge weight, size, and cost, a battery with nickel tendrils was soldered directly to the electronic board (Fig. 3).

Fig. 3 Power source

To avoid user contact with the interior of the sensor, a switch (Fig.4) has been implemented that intuitively and easily activates the device by mechanically changing the position with one finger.

Fig. 4 Switch for sensor activation

The DCS (Fig.5) is designed to collect measurement data and transfer them to the SA for further processing, calculations, and visualization. It was assembled in a plastic case. The housing contains a microcontroller with a built-in wireless network module with the LoRaWAN protocol, a memory card for storing the measurement data, a Wi-Fi data transmission module (DTM), a modem for receiving the data accumulated in the memory card, and a Wi-Fi data transmission module that transmits data to the server via 3G/4G networks, and a built-in high-capacity battery for powering the microcontroller and modem. The DCS is powered by 230 V and in case of its absence, it instantly switches to power from the built-in battery.

Fig. 5 Data collection station

3.2 Software Development (SD)

To operate the Atmega328p microcontroller with sensors and DTM, the software was written in C++ in the VisualStudio Code: Platformio environment. To be ready to receive and store the codes in the microcontroller we first loaded the standard software "Bootloader", which allows the microcontroller to receive and store all new codes for later use. The bootloader and the program code were written to the USB-TTL microcontroller with the programmer shown in Fig. 6.

Fig. 6 USB TTL programmer adapted for series programming

To write the codes on the board special contacts are used to connect to the programmer stings. The process of connecting the programmer stingers to the PM pins is shown in Fig. 7. The Arduino IDE software is used to load the standard Bootloader into the Atmega 328p microcontroller. After loading the Bootloader, the microcontroller can accept and store in its memory more complex and PM-targeted codes, which were developed in Visual Studio software with the plug-in for working with the various series of energy-efficient microcontrollers Platformio. All data from the PM flows to a server application developed in HTML, PHP, CSS JavaScript, and installed on the laptop. The interface of the server application is shown in Fig. 8.

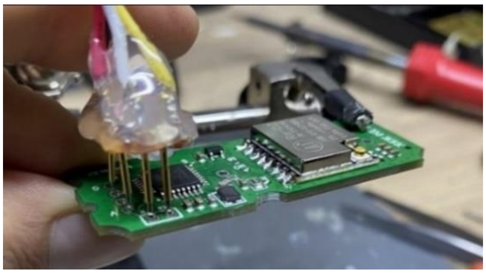


Fig. 7 Uploading software to the WMS via USB TTL programmer

Fig. 8 Window interface with received data from the sensors

3.3 Sensor testing

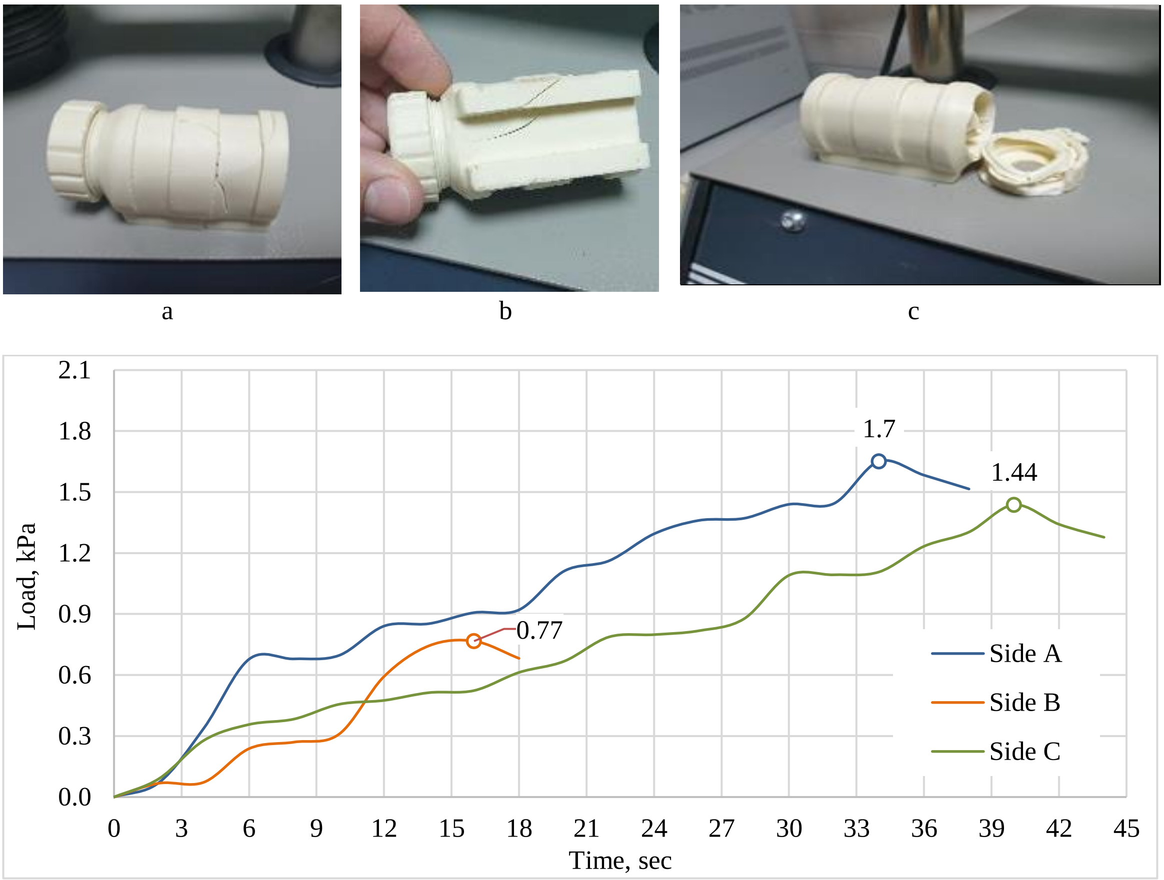
To confirm the durability of the housing, experimental procedures included tests for water resistance, integrity, and load resistance. For the water-resistance test, the case was completely immersed in water (Fig. 9).

Fig. 9 Water resistance test

Before being immersed in water, the assembled enclosure was weighed and a wipe was placed inside the housing. Since moisture may penetrate inside the housing, the wetness of the wipe can be easily detected visually.

During the integrity test, the tested housing was dropped without acceleration from heights of 1, 1.5, and 2 m. The drop height was calculated from the floor to the bottom side of the housing. Thus, the tests were carried out for 3 sides of the body. No cracks were found in the integrity tests, but only small dents that did not affect the internal structure of the case.

Three tested housing were destroyed during compression tests, and the varying area of the press plunger in the compression results was taken into account (Fig. 10).



a b c

Fig. 10 Cylindrical housing compression load graph under hydraulic press on 3 sides of the casing: a) Side A; b) Side B; c) Side C

4. TESTING PROCEDURE

The testing procedure included the studies of the process of concrete strength gain in using different instrumentation, such as IPS-MG-4.03 shock-pulse sclerometer, hydraulic press, and wireless sensors. The marketable concrete with the grade of B25 M350 was tested, and the data obtained in the tests can only be used for this concrete with the same consumables [13].

[9] standard specifies that there are 4 steps in the method of calculating the current strength of concrete according to its maturity: 1) Establishing the maturity-strength relationship (in the laboratory): 2) Embedding maturity sensors inside the formwork (at the construction site); 3) Reading

concrete maturity values with sensors (on-site); 4) Data analysis.

17 cylindrical specimens with a diameter and height of 15 cm each were prepared for the test similar to [14].

15 specimens were tested on compression by the hydraulic press under ambient conditions (the lab was omitted to provide both small and large specimens with equal curing conditions), three specimens each at 1, 3, 7, 14, and 28 days. The temperature sensors were dipped into the remaining 2 specimens to measure the curing temperature of the concrete in the specimens every 0.5 hours up to 28 days (Fig.11). The ambient temperature at the beginning of the measurements was around 20 °C. The obtained temperature history was then used to calculate the maturity indexes according to the Nurse-Saul maturity function shown in Eq. 1 was used.

$$\boldsymbol{M(t)=\sum(T_a-T_0)\cdot\Delta t} \quad (1)$$

where:

$M(t)$ – the temperature-time factor (or maturity index) at age t, degree-days, or degree-hours;

Δt – a time interval, days or hours;

T_a – average concrete temperature during time interval Δt, °C;

T_0 – datum temperature (below which no cement hydration reaction takes place), °C.

The maturity function is a mathematical expression that uses the measured temperature history of the cement mixture during the curing period to calculate an index indicating maturity at the end of that period.

Fig. 11 Cylindrical samples

The purpose of these tests was to derive the maturity-strength relationship of concrete. This relationship is expressed as a logarithmic function, and it is used to calculate the current strength of concrete in a real structure when the same composition is used. To simulate a real structure with the same concrete composition, two large 50×50×50 cm cubic specimens were prepared, in which temperature sensors were also immersed (Fig.12).

Fig. 12 Large samples

Using the temperature history measured at a frequency of 0.5 hours, concrete maturity indexes were calculated using the same Eq. 1. Then, by substituting these values into the derived logarithmic function (i.e., maturity-strength relationship), the in-situ concrete strength values in the structure on the 1, 3, 7, 14, and 28 days of curing were determined. On the same days, large samples were tested by a non-destructive Shock-pulse method using an IPS-MG4 sclerometer. Further, using the average values of the strength obtained by three different methods, graphs of concrete strength gain and graduation dependences were plotted.

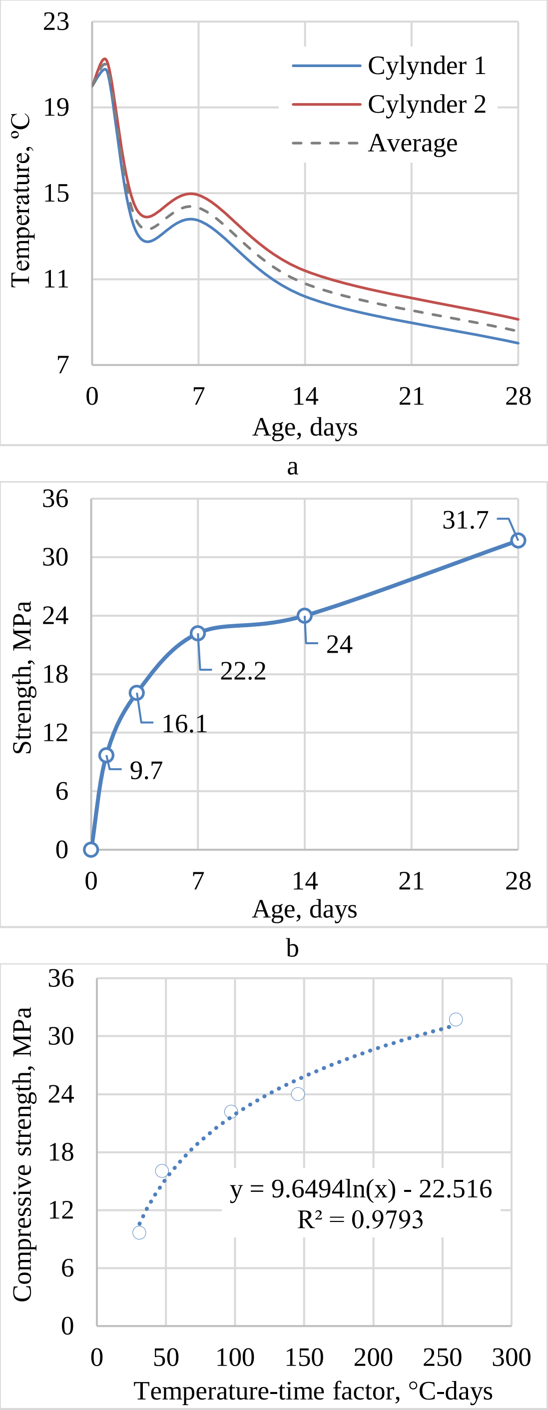
5. RESULTS AND DISCUSSIONS

The results of testing the cylindrical concrete specimens are shown in Fig. 13. The curing temperature in two cylindrical specimens was monitored for 28 days. The ambient temperature at the end of the measurements was around 8 °C.

As can be seen in Fig. 13a the highest curing temperature is observed in the first 3 days (21 °C), then there is a sharp decline with a slight increase in temperature on the 7th day. Then the curing temperature on the 28th day obtained a value of ambient temperature, which was around 8 °C.

Fig. 13b shows a graph of the strength gain in the cylinders. As a consequence, a sharp increase in strength is observed in the first 3 days, after which a gradual rise is observed.

The maturity indexes calculated according to Eq. 1 for the days 1, 3, 7, 14, and 28 were equal to 30.88, 47.24, 97.29, 145.53, and 260 °C-days respectively. By superimposing and plotting these values together with the strength values on the same days of curing, the maturity-strength relationship was derived as shown in Fig. 13c. The dependence obtained has a fairly high coefficient of determination equal to 0.9793, which indicates its further applicability in the calculation of the strength of the real structure (i.e., large cubic specimens used in the current study) from the same composition of concrete.



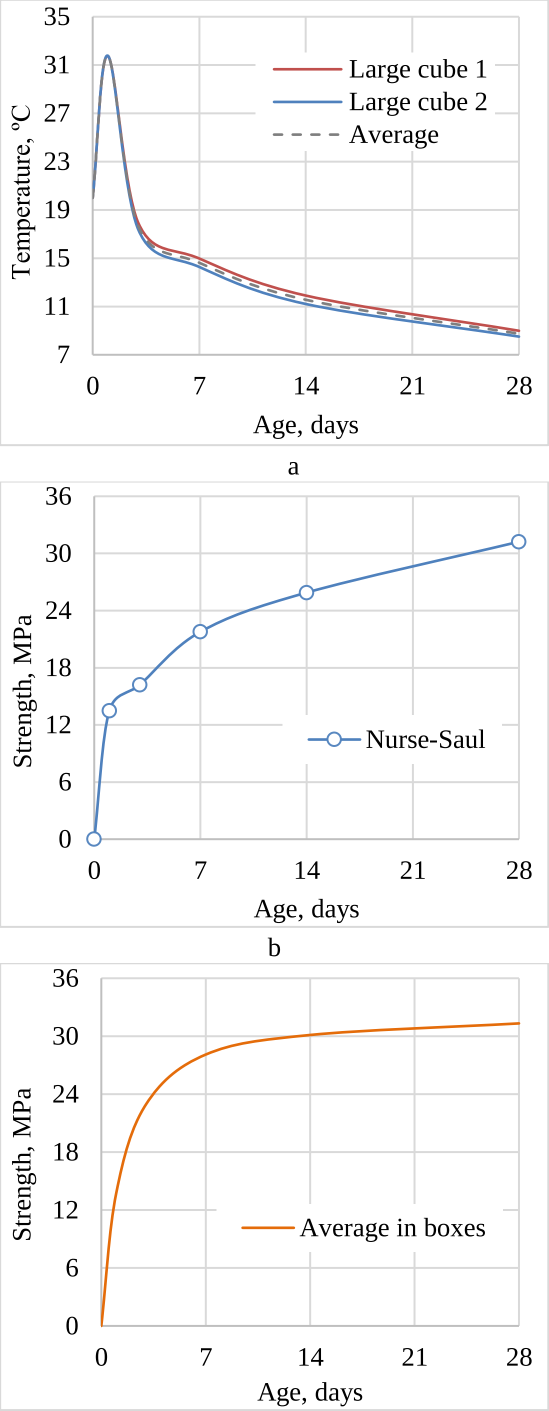
a

b

c

Fig. 13 Test results of small specimens: a) curing temperature regime; b) strength graph of cylinders; c) maturity-strength relationship

The test results of large specimens are shown in Fig. 14. The average values of curing temperature of Fig. 14a were used to calculate the in-situ maturity indexes. The latter was used in the estimation of the strength values by the maturity-strength relationship derived previously (Fig. 13c) to finally obtain the Nurse-Saul strength graph (Fig. 13b). Fig. 13c shows the Shock-pulse strength graph.



a

b

c

Fig. 14 Test results of large specimens: a) curing temperature regime; b) Nurse-Saul strength graph; c) Shock-pulse strength graph

As shown in Fig. 14a, compared with the curing regime of cylinders, the temperature increase on the first day of hardening of the large specimens is more intense. In the first 2 days the temperature rose to 32 °C, then gradually decreased to a temperature of

8 °C. This can be explained by the massiveness of large specimens compared to small ones. Concrete maturity values at 1, 3, 7, 14, and 28 days were calculated in a similar way for large specimens. By substituting these values into the maturity-strength relationship obtained above, the strength values on the same day were calculated [15-16], from which the strength gain graph was plotted (Fig. 14b).

According to the test results of large specimens by the Shock-pulse method (Fig. 14c), during the first 7 days, the concrete strength rose intensively, after which it smoothly transitioned to stabilization. To compare the results of the indirect methods obtained above with the direct methods of control, compression tests of small cubic specimens in a hydraulic press were conducted and their results are presented in Fig. 15.

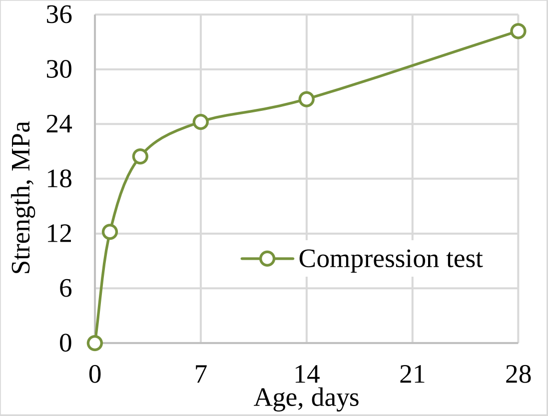


Fig. 15 Test results of small cubic specimens

The strength gain curve of small cubic specimens has a similar outline to the one obtained by the maturity method. But the strength value at 28 days is noticeably higher. For a visual comparison of the results of the indirect (maturity method (N-S), shock pulse method (S-P)) and direct (compression cube specimens (C)) method, their strength gain curves are combined into one graph and the graduation dependences between these methods were derived (Fig.16-17) [8].

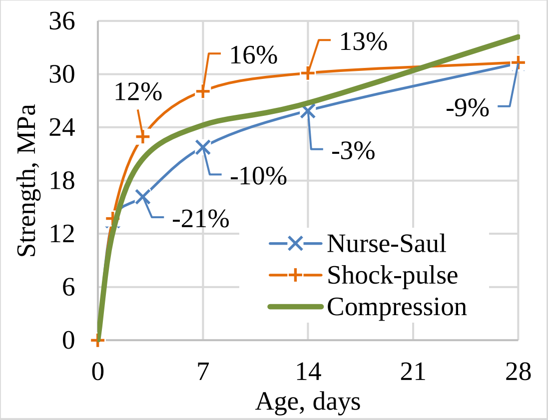


Fig. 16 Strength gain graphs

The graphs above show that S-P strength results are greater than C by 13.5 % on average. And the strength results of N-S are lower than C by 11 %.

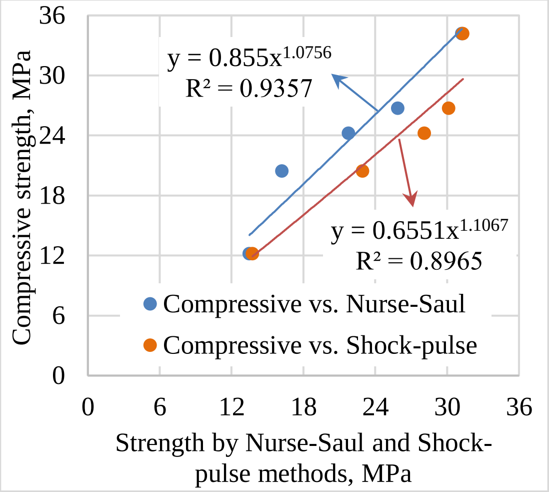


Fig. 17 Comparative analysis of results: graduation dependence of C vs. N-S, and C vs. S-P

From the graduation dependences above represented by power, functions are seen that the strength values obtained by the Nurse-Saul method using the proposed embedded sensors showed a greater convergence with compressive strength values than those of Shock-pulse. This is explained by the coefficients of determination amounted to 0.9357 for N-S and 0.8965 for S-P respectively.

6. CONCLUSION

The current study demonstrated the possibility to develop an inexpensive wireless embedded maturity sensor able to monitor the curing temperature and estimate the concrete strength. The sensor and data collection station were built based on an Arduino microcontroller and various integral modules. The server software was built using HTML, PHP, CSS, and JavaScript languages, where the Nurse-Saul maturity method was programmed. The developing process is easy to handle and replicable.

The performance of the proposed sensor solution was confirmed by comparison with conventional direct and indirect techniques for concrete strength testing. Thus, the maturity sensor results have a greater convergence ($R^2 = 0.9357$) with the compression test than that of the shock-pulse test ($R^2 = 0.8965$), which indicates its applicability as an alternative concrete strength technique.

The developed solution has entered the State Register of Measuring Instruments of the Republic of Kazakhstan and was recognized as a measuring device for temperature-strength control [17]. The peculiarity of the developed sensor is the continuous collection of data on the state of reinforced concrete structures, up to the battery discharge, even after the end of monolithic works. This property of the sensor contributes to the accumulation of big data on the server, representing a huge amount of various quantitative and qualitative information about the rate of strength gain of reinforced concrete structures, the composition of the concrete mixture, environmental conditions, and other parameters.

7. FUNDING

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