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Potential applications of maturity sensors for monitoring geotechnical structures and their setup methods

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ABSTRACT: Recent years demonstrated the widespread use of maturity sensors for monitoring structural elements of monolithic building frame resulting in the development of many instructions on their application, which does not apply to the monitoring of geotechnical structures. This paper presents potential use cases and setup methods of embedded maturity sensors. Proposed instructions can be used as a method statement for the real-time strength control of concrete foundations and underground walls.

1 INTRODUCTION

Concrete is one of the basic and widely used materials on the construction site. Many processes have to wait for this building material to reach its strength, which can lead to postponement under negative circumstances. For this reason, the goal of timely achievement of strength or design strength after 28 days plays a very important role in reducing the time of construction. It is worth noting that the priority in the accumulation of strength has massive structures, lying below the net floor level of the first floor, taken as 0.000 m. Solid and strip foundations, deep and shallow foundations, retaining walls, crossbeams, etc. are considered massive constructions. The processes inside the concrete and measures such as summer watering and winter heating (concrete care) to maintain favorable conditions are therefore given close attention(Christiaan 2019).

The process of concrete strength gain is a set of physical and chemical processes at the time of hardening. For example, concrete curing is accompanied by an exothermic reaction and its persistence for 1, 3, 7, 14,and 28 days with a rise at the beginning and a subsequent decrease in temperature at the end. The temperature graph arising from the exothermic reaction is the standard, approved by the destructive method of quality control of cubic specimens at the achievement of indicators for 28 days, and any discrepancy suggests a deviation from the mixing technology of concrete or the subsequent care of him(Jung 2009; Rudeli 2015).

In connection with the above, some regularities apply to new methods of monitoring and controlling concrete curing. In turn, the new monitoring methods involve the use of high-precision sensors and sensors that track various indicators during the curing process. In the information environment, such electronic devices are called temperature sensors or sensors of concrete maturity. The second name is rather more scientific than the first because it is derived from a method (ASTM 1998)and describes the nature of the method by reference to the temperature-time factor (TTF). (ASTM 1998)regulates two fundamental formulas in the basis of the method for calculating the temperature-time index known as Nurse-Saul (Formula 1) and Arrhenius (Formula 2). It is worth noting that the maturity method Nurse-Saul is widespread in the market of electronic devices (Jung 2009). The advantage of this method is the obvious relationship between concrete strength and the hydration temperature of the cementitious paste.

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$$M(t) = \sum_{0}^{t} (T_a - T_0)\Delta t \quad (1)$$

where M(t)= temperature-time factor, ºC-days or ºC-hours; Δt = time interval, days or hours; T_a = average concrete temperature, ºC, during the time interval, Δt; and T_O = datum temperature, ºC.

$$t_e = \sum e \frac{-E_a}{R} \left(\frac{-E_a}{T_a} + \frac{-E_a}{T_s} \right) \Delta t \quad (2)$$

where t_e= equivalent age at a specified temperature, T_s, days or hours;

E_a= activation energy, J/mol; R = gas constant, 8.31 J/(K*mol);T_a= average temperature of concrete during the time interval, Δt, K; T_s= specified temperature, K; and Δt = time interval, days, or hours.

The current market for electronic devices offers various variants of maturity sensors, both foreign and domestic, and assemblies (Figure 1).

SmartRock (Canada) | Concrete Sensors (USA) | Command Center (USA) | Con-Cure Nex (USA)

Figure 1. Examples of existing concrete maturity sensors.

Several parametersare considered when choosing a maturity sensor, such as the presence of a wireless or wired network, the measurement of various indicators, the minimum and maximum temperature range, the accuracy of the error and measurement interval, as well as the data transmission range and battery life(Utepov 2022).

During the existence of maturity sensors, the development of the electronic component has gone far beyond the technical regulations and regulatory and technical documentation for their installation and operation. Based on the analysis of existing literature sources, it can be concluded that the works (Christiaan 2019; Jung 2009; Rudeli 2015), where concrete maturity sensors were used, mainly refer to the building framework, that is, columns and floor slabs lying above zero level of the first floor.During the existence of maturity sensors, the development of the electronic component has gone far beyond the technical regulations and regulatory and technical documentation for their installation and operation. Going back to what was said before, the priority in strength gain is given to massive structures lying below the level of the clear floor of the first floor; the problem that emerges in this article is the following. Concrete maturity sensors should be installed in the areas withthe slowest strength gain and the most stressed areas(Nurakov 2020).In this connection, as the main attention is paid to the typical floors above the 0.000 m elevation, the moment of installation of concrete maturity sensors and operation, in the form of instructions, not to mention technological charts has been missed, which forms the purpose of this article. The authors offer effective methods of installation and operation of concrete maturity sensors in the construction of geotechnical structures (foundations, retaining walls, etc.) (Awwad 2019; Zhussupbekov 2019).

2 USE CASES

Long-term durability is very often discussed in the construction of reinforced concrete structures. Various sensors and devices for monitoring the condition of reinforced concrete structures are used for this purpose. Thus, in the example of tunnel construction, the focus is on concrete life-cycle monitoring sensors. Depending on the environment in which the structure is operated, the installation of sensors plays a very important role. The importance of technology compliance and subsequent monitoring is described in (Feng-Hui 2000), where an example of the collapse of parts of tunnel interior walls is given. The colossal damage to public property and the threat to ordinary citizens is the result of an untimely inspection of the structure. The authors decide to use a robotic automatic tunnel inspection system compatible with sensors in the concrete, but the question of their design when the sensors are immersed in the body of the concrete remains open. The behavior of sensors during construction of the tunnel is considered in (Bursi 2016), where the performance of built-in and externally installed sensors are compared. It is worth noting that the difference in readings was 50%. To give an example of other constructions, we can highlight works related to massive foundations (Utepov 2022).Another important factor deals with the monitoring of deformation and temperature of reinforced concrete pile foundations, namely, the careful installation of sensors for obtaining correct data. Attention is paid to such secondary, but not unimportant factors as the transportation of sensors and the protection of sensors during the process of concreting foundation wells. Some works (Qin 2014) mention the use of several sensors to monitor the condition of reinforced concrete structures. An interesting point when conducting experiments of this type is the compatibility of electronic devices or their location relative to each other. The construction of massive structures or large volumes of concrete has always had its nuances. This problem is discussed in (Chang 2012), where a temperature difference exceeding the permissible limit is considered. This phenomenon is fraught with cracking, which leads to the subsequent penetration of moisture and further corrosion of the reinforcement (Lukpanov 2021; Lukpanov 2021).The prerequisites for determining the location of temperature sensors are given in (Ye Utepov 2019). This method can be applied to temperature sensors (Utepov, Tolkynbayev 2022; Utepov, Tulebekova 2022), which may not be applicable in other cases, but the validity of this methodology can form the basis for instructions or process maps for installation and operation of temperature sensors. Thus, when examining the sources currently available, it can be concluded that the given examples of using sensors to monitor phenomena occurring in concrete contain information for theoretical analysis, while attention to the features of installation in practice, especially on geotechnical structures and structures, is not adequately paid.

3 MATURITY SENSORS SETUP METHODS

The installation process for any sensor on a construction site begins with a secure attachment to the structure. Before installation begins, the depth of the sensor or its components, such as a cable with a sensor at the end, must be determined. Here is an example of fixing a concrete maturity sensor to working rebar (Figure 2).

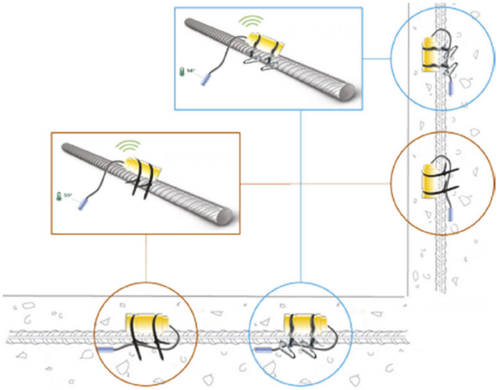

Figure 2. Example of mounting and fixing the concrete maturity sensor on horizontal and vertical reinforcement.

According to the figure above, the sensors are installed according to a certain scheme on the longitudinal (working) and transverse (distribution) fittings. Fixing in the field is done with a wire or a clamp. Depending on the strength of the signal transmission at the construction site, the sensor is immersed to a greater depth than the protective layer of concrete. This distance from the surface of the housing to the paved mixture must be strictly maintained, as required by the technology of the concrete mix. If the casing is leaking or the signal transmission is poor, only the cable with the sensor at the end is immersed, while the main part of the cable is placed on the surface. The contact of the sensor with other surfaces, except for the concrete mixture, is excluded, as it may lead to distorted data. It is worth noting that when pouring and compacting the concrete mixture, you must be careful because the vibrating machine can damage the sensor. The transmission of measured data goes locally within the range of the sensor and does not apply to the entire structure. In this regard, the pitch and depth of the sensors are very important. The logic of the schematic location of the sensors on the example of a strip foundation on pour piles, a foundation slab, and a retaining wall is given in the sections below.

In the case of a cast-in-place pile, the sensors are installed at the initial stage when the frame is tied in because access to the sensor is restricted after the frame has been sunk into the borehole. Depending on the depth of the pile, the required number of sensors is selected. Due to the location of sensors under the soil layer the signal transmission power can significantly decrease, in this regard it is reasonable to sink only the cable with the sensor into the concrete body and fix the body itself on the armature outlet above the ground (Figure 3). When assembling the strip foundation formwork, the sensor housing can be both in and out of the concrete body. In this case, it is advisable to install the sensors on the transverse reinforcement, so that the cable with the sensor at the end is located in the center of the structure (Figure 3).

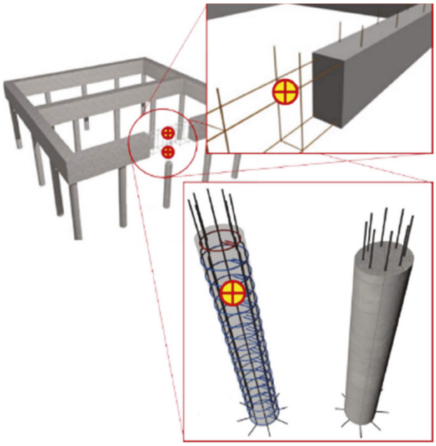

Figure 3. Location of sensors inside the strip foundation on pour piles.

The foundation slab is the most massive structure when installing sensors for monitoring. At this scale, it is necessary to install sensors at several heights (Figure 4).

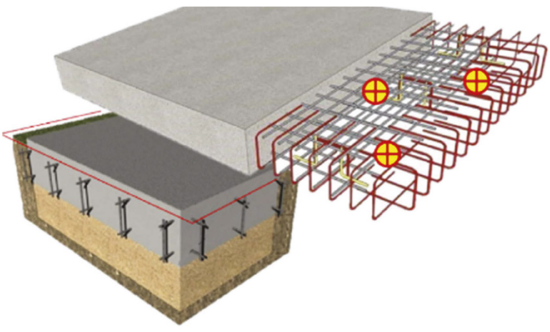

Figure 4. Sensor location inside the foundation plate.

In the case of installation of sensors in structures at height, it is necessary to install scaffolding, decking, and scaffolding with enclosing structures. An obvious example of installing sensors at height is retaining walls, which come in different heights and thicknesses. Alternatively, sensors are installed as in the case of pouring piles at the initial stage of tying the reinforcement cage, and then the finished cage is connected to the outlet of the reinforcement at the bottom of the foundation (Figure 5).

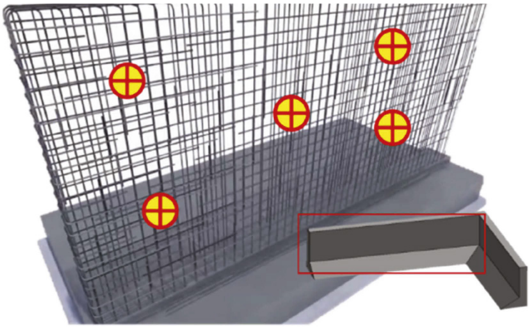

Figure 5. Sensor location inside the retaining wall.

4 CONCLUSIONS AND RECOMMENDATIONS

Based on various examples, based on the existing sensors on the market for concrete monitoring, the following generalized conclusions and recommendations have been formulated, which apply to the installation of any sensor, regardless of its purpose:

1. Subsequent monitoring of the design may be accompanied by the following hazardous and harmful factors:
- increased or decreased temperature of the air in the working area;
- increased air humidity, noise and vibration level;
- location of working place at a considerable height relative to the surface of the ground (floor, overlapping);
- insufficient illumination of the working places;
- physical overloading.

2. To ensure the reliability of the results obtained, you should pay attention to the following points in the operation of the sensors:
- completeness and reliability of attachment of parts;
- serviceability of the sensor components, protective sheathing, and presence of mechanical damages;
- the integrity of insulating parts of the sensor housing;
- serviceability of the sensor activator (free switching on and off before the beginning of work);
- serviceability and connection of the data acquisition station, if any, to the socket with voltage (change of light indicators);
- location of the data collection station in a hard-to-reach and low-traffic location for safety and uninterrupted operation.

The results are reflected in the technological schemes (Figures 2–5), which show the proposed locations for the installation of sensors. The number, pitch, and depth of installation may vary depending on the size, massiveness of the structure, and the peculiarities of the geotechnical construction. It is worth noting that the issue of using different sensors to monitor one structure remains open, which makes it possible to continue the development of technological schemes and maps when several sensors work in one working field.

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