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AUTOMATING THE CONSTRUCTION OF BUS BAYS WITH REINFORCED CONCRETE

Summary. When renovating intensively used bus bays, roads and squares, the need for their periodical closure to traffic during the period of works is inconvenient. In the case of concrete surface repairs, this timeline is additionally elongated due to the standard requirement of a 28-day curing period. The Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology has investigated the prototype RoadTronic robot to make slabs reinforced with a mesh of glass fibre rods. Process automation permits the application of rapid-setting CSA-based (calcium sulphoaluminate-based) cements, which achieve a compressive strength of over 20 MPa after just 1.5 h. The good properties of such cement have been confirmed by several years of use on the runway at Seattle-Tacoma Airport. Preliminary tests of the early compressive strength of Rapid Set® CSA-based concrete performed at the department, as well as calculations of guaranteed strength, indicate that young concrete can transmit operational load after just 4 h from mixing with water. The investigated solution assures a complete slab following one passage of the robot. This would permit the removal of the existing layer during reduced vehicle traffic, e.g., between 06:00 and 22:00, and the execution of a new abrasive concrete layer by 02:00, so as to restore regular traffic at 06:00.

Keywords: automation; CSA cement; bus bays.

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1. INTRODUCTION

The applied concrete laying systems, both in building construction and in road construction, allow works to be executed with complex automation. The preparation of the concrete mix, as well as its transport, pumping and compaction, is usually performed using mechanical devices, with minimized manual labour. This refers to typical Portland cements. When constructing new facilities, there are usually no problems in ensuring even a 28-day curing period for such concrete in order to achieve its standard strength [5]. In the case of refurbishment, however, particularly in respect of intensively used bus stops and bays, involving severe traffic disruption, even repairs taking a few days can become a significant nuisance.

Rapid-setting CSA cements are characterized with high early strengths and allow for load placement on the new concrete elements after only a few hours of curing [3,6-9,13,15]. An example can be found in the refurbishment of the runway at Seattle-Tacoma Airport, where aircraft touched down just 4 h after the completion of concrete works [2].

CSA cement is a mineral hydraulic binder with rapid early strength build-up (e.g., over 35 MPa after 8 h from reaction with water), small contraction and high resistance to sulphates, [1,5]. The main CSA components include anhydrous CSA ($4CaO\ 3Al_2O_3{\cdot}SO_4$), dicalcium silicate ($2CaO{\cdot}SiO_2$) and gypsum ($CaSO_4{\cdot}2H_2O$). When CSA cement is mixed with water, a quick reaction occurs between the anhydrous CSA, gypsum and calcium hydroxide, involving dynamic heat generation and intense generation of ettringite, a mineral that causes high early strength, with full strength guaranteed by the manufacturer after three to seven days [7,14].

Due to the immediate setting of CSA cement, specialist (highly efficient) execution is required. Systemic equipment for concrete works has a limited range of application. There is a need for mechanical cleaning of all tools every few minutes - up to 30 min. This prevents the application of many typical mechanical devices for concrete works, as well as standard organizational solutions, and usually involves a high share of manual labour.

The development of digital control and automatic devices offers great potential with regard to improvements in the quality of works, particularly in the case of complex projects. At the same time, humans are relieved from hard physical labour. State-of-the-art control and automatic devices assure precise execution of all planned works. Therefore, at the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology, as part of the research on streamlining construction processes involving ja-wa technology (Polish: unilateral material application with travelling automatic device), works were undertaken on the prototype RoadTronic robot for making concrete slabs reinforced with a mesh of glass fibre rods.

The proposed solution has a completely different approach to slab execution. With digital control of particular working assemblies, the robot simultaneously places the reinforcement mesh and the coating to secure it against water evaporation, as well as doses components, prepares the concrete mix, transports it, performs extrusion grouting, compacts it and then forms the surface on the belt of the element thus formed [16]. The process involves systematic mechanical cleaning of all surfaces in contact with the setting concrete. Slabs made using rapid-setting CSA cement are adjusted to high loads from vehicle traffic (KR 7 traffic category; over 2,001 standard 100-kN calculated axles per day).

Further on, we analyse the technology and operation of the prototype RoadTronic robot, with the presentation of selected properties of young CSA-based concrete, as well as preliminary test results and calculations of guaranteed strength.

2. EXPERIENCE WITH THE REFURBISHMENT OF THE SEATTLE-TACOMA AIRPORT RUNWAY

Seattle-Tacoma Airport with 1,200 operations per day (take-offs and touchdowns in total), is the 15th-largest airport in the US. The original 16R/34L runway, with a length of 2,873 m, was constructed as a concrete runway in 1969. An expert study in 1991 indicated the need for the refurbishment of many slabs. It was impossible to shut the runway down for the time of refurbishment, as this was the only runway available. Pursuant to a Rapid Set® concrete analysis in respect of requirements imposed by the Federal Aviation Administration (MD-11 for 20 years of life, as well as 1,150,000 take-offs and touchdowns), and pursuant to tests of pilot slabs, it was determined that concrete made on the basis of CSA cement achieves the necessary strength after 4 h from reaction with water.

A decision was made on the gradual replacement of the damaged slabs. At 23:00, the runway was shut down to remove the damaged slabs, adjust the subgrade and make new slabs (Figure 1). The works had to be completed by 03:00, so that the first plane could touch down at 06:30. In the period 1994-2005, using a tested technology and following a detailed work organization schedule, out of 1,892 existing slabs, the replacement involved 531 slabs (with dimensions of approximately 6x6 m), mainly in the central areas of the runway, which transmitted the highest loads from planes touching down [2,12].

Fig. 1. Concrete works at Seattle-Tacoma Airport using a Rapid Set® mix [7]

In August 2012, the 16R/34L runway was closed for refurbishment (this was possible, as an additional runway had been built). This was an opportunity to carry out detailed tests in the context of the long life of the CSA-based concrete slabs exposed to early loads. A total of approximately 30,000 m^3 of original slabs was replaced with new CSA-based slabs, which constituted 79.1% of the slabs refurbished. Following between seven and 18 years of operation, only 20 CSA-based slabs proved to be damaged. The failure rate totalled 3.8% vs. the rate of 35.5% for original slabs based on Portland cement (recalculated for the same operating period).

When the additional runway was constructed in 2010, the 16R/34L runway underwent a replacement of an additional 177 slabs, namely, 29.1%, using the “three-day mix” Portland cement. After three months to two years of operation, 56% of these slabs were damaged, compared to 8% of the Rapid Set® slabs (recalculated for the same operating periods).

This experience points to the good operational properties of CSA-based concrete, also in the case of early use, following 4 h from reaction, with full load.

3. ROADTTRONIC TECHNOLOGY FOR MONOLITHIC REINFORCED CONCRETE SLABS

The RoadTronic kit comprises:

- analytical algorithms for control of particular assemblies, with monitoring of ambient conditions
- chassis with a frame to stabilize subassemblies
- automatic paver kit

During the works, appropriate to the changing conditions, especially temperature and rapid CSA cement-based concrete strength build-up, the control, monitoring and quality control of the automatic mobile chassis with subassemblies are assured. In light of the material embedding site and calculation results, with real-time coordination, the digitally controlled assemblies continuously prepare and embed materials at strictly defined times, with the necessary production intensity. Continuous upkeep with embedding times conditions the correct monolithic properties of concrete. Hence, the control includes the necessary performance and pressure of mix extrusion, as well as the speed of the chassis with the assemblies.

The chassis frame houses the automatic paver kit (Figure 2), which executes the slab (1) while continuously moving the works and the entire device in direction (2).

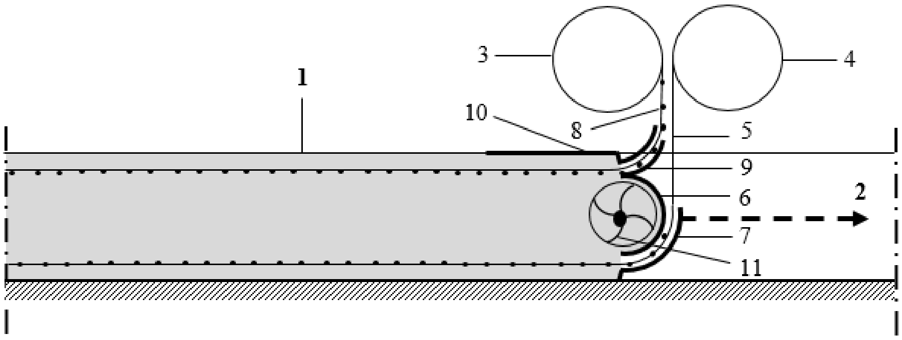

Fig. 2. Paver kit diagram (see description in the text)

The robot's toolkit includes two unfolding rollers (3 and 4) with a reinforcement mesh of glass fibre rods. Mesh (5) at the bottom is input from the front, between the paver casing (6) and the front guide (7), which, due to its form, assures a mesh distance (reinforcement cover) from the bottom of the slab that is formed. The other mesh (8), at the top, is input over the paver casing (6) with a guide (9) under the top disc (10), which assures correct mesh placement vs. the surface of the slab formed. Together with the entire robot movement in direction (2), and successive placement of the reinforcement mesh, water is added to the concrete mix and spread on the entire slab width, with extrusion grouting and compaction with feeder blades (11). Top disc (10), with a greater width than the impact of the extrusion pressure and compaction of the fresh mix, forms and smoothens the top surface of the slab. As a result, the entire slab is completely executed in one pass of the robot.

Rapid-setting CSA cement causes the need for frequent mechanical cleaning of the tools and equipment, usually not less frequently than between a few minutes and half an hour. This issue has also been solved by the RoadTronic technology owing to continuously moving elements, which assure permanent cleaning of all surfaces in contact with the concrete mix

4. CSA CEMENTS AND WORKS EXECUTION

CSA cements are manufactured with grades 42.5, 52.5, 62.5, 72.5, 82.5 and 92.5 (in this case, the values indicate compressive strength values achieved after seven days). CSA cements, which are stored in dry places in sealed packaging, have a shelf life of 12 months. Major manufacturers of rapid-setting cements are located in the US and China.

It must be pointed out that obtaining CSA in the reaction requires full hydration, which occurs with minimum water/cement proportions of $w/c > 0.36$ [15]. In proportions of $w/c \leq 0.61$, 100% of the water reacts with the CSA cement. Aggregates are composed on similar terms as in Portland cements, whereas the minimum CSA volume totals 300 kg/m^3 of concrete mix [3,8].

In order to achieve the intended strength parameters, CSA concrete must be prepared and embedded at outdoor temperatures within the range between 7°C and 32°C (at lower temperatures, the setting process occurs at a much slower rate, while, at higher temperatures, with additional hydration heat, ettringite may become decomposed). At a temperature of 20°C, setting occurs after only 15 min or up to several minutes later [3]. With citric acid used as a retardant, the onset of the setting time can be postponed by 15 min.

CSA cements are principally applied in necessary short-term repairs and urgent works.

The onset of CSA cement setting, occurring usually after several minutes, requires the execution of non-standard works, as the processes of setting and curing occur almost immediately following the addition of water. Hence, concrete teams must be appropriately trained and provided with the suggested equipment. They must execute works according to a strictly defined organization of works. Concrete must not be vibrated after it has started to set and the surface must be secured against evaporation. During the works, tools must be systematically cleaned, usually not less frequently than every 30 min. The mixers and other equipment used must also be mechanically cleaned at similar time intervals.

5. VARIABILITY OF CONCRETE COMPRESSIVE STRENGTH DURING THE CURING PERIOD

Concrete strength with time depends on the type of cement, temperature and curing conditions [4]. At an average temperature of 20°C and curing according to EN 12390 [10], pursuant to EC2 [4], it can be assumed that the characteristic concrete compressive strength $f_{ck(t)}$ at age t totals:

$$f_{ck(t)} = f_{cm(t)} - 8\text{MPa for } 3 < t < 28 \text{ days.} \tag{1}$$

According to EC2 [4], more precise values, particularly with $t \leq 3$ days, must be specified pursuant to tests. In turn, average concrete compressive strength depending on the age can be estimated according to the following equation:

$$f_{cm(t)} = \beta_{cc}(t)\, f_{cm}, \tag{2}$$

$$\beta_{cc}(t) = \exp\left(s\left(1 - \exp\sqrt{\frac{28}{t}}\right)\right), \tag{3}$$

$f_{cm(t)}$ - average concrete compressive strength at the age of t days
f_{cm} - average concrete compressive strength after 28 days

$\beta_{cc}(t)$ - coefficient depending on the concrete age
t - concrete age in days
s - coefficient depending on the cement type.

In the case of the application of CSA cements, where fresh concrete in the ceiling needs to be immediately deprived of formwork, the *ja-wa* system already requires information on the characteristic concrete compressive strength $f_{ck}(t)$ at the age of $t \geq 1.5$ h.

When analysing the strength of the samples tested (three samples each, on nine occasions, from 1.5 h up to seven days, at the aforementioned laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology), major differences in the results, with a standard deviation of $s = 1.38$, occurred for samples with a concrete age of 8 h (from mixing the components with water). The average strength of three samples totalled $f_{cm(8h)} = 31.5$ MPa. A *t*-Student test was applied to check whether the EC2 condition [4], in the case of 95% of samples in the lot achieving the characteristic strength, was met. For samples with strength $\delta = 4$ MPa lower than average $f_{cm(8h)}$, the test statistic value $t_{obl} = (\delta/s)\sqrt{n-1}$, following substitution totals $t_{obl} = 4.099$, which is higher than the *t*-Student distribution quantile of $t_{(0.95,\ 2)} = 2.920$. Therefore, the following assumption was adopted:

$$f_{ck(t)} = f_{cm(t)} - 4 \text{ MPa, for } 1.5 \text{ h} \leq t \leq 168 \text{ h.} \tag{4}$$

Pursuant to the results of the sample strength tests (at times with 1.5-h intervals up to several days, Table 2), the function of average compressive strength was defined for concrete based on CSA cement depending on concrete age *t*, according to:

$$f_{cm(t)}^{CSA} = f_{cm(168)} \{1 - [\alpha_{(t)}]^{0,074}\} - 1, \quad \text{for } 1.5 \text{ h} \leq t \leq 168 \text{ h,} \tag{5}$$

$f_{cm(t)}$ - average concrete compressive strength at the age of t h (hours)
$f_{cm(168)}$ - average concrete compressive strength after 168 h (seven days)
$\alpha_{(t)}$ - coefficient depending on concrete age, $\alpha_{(t)} = 168/t$ (t - analysed concrete age from mixing dry components with water, in h)

Table 1 present the results for fresh CSA-based concrete compressive strength determined in the tests, as well as calculated results pursuant to Equations (4) and (5).

Table 1
Strength values for Rapid Set® fresh concrete pursuant to tests and calculated according to Equations (4) and (5)

Test of concrete aged t, h	1.5	2	3	4	8	24	48	72	168
Average strength from tests f_{cm}, MPa	24.9	27.3	29.9	31.5	35.1	37.9	40.2	41.5	44.3
Average strength, according to (4) $f_{cm(t)}$, MPa	24.8	26.1	27.9	29.2	32.1	36.4	39.0	40.4	43.3
Characteristic strength values, according to (5) $f_{ck(t)}$, MPa	20.8	22.1	23.9	25.2	28.1	32.4	35.0	36.4	39.3

According to Table 1, average compressive strength values $f_{cm(t)}$, calculated pursuant to Equation (4), are lower than the strength of analysed samples $f_{c(t)}$ in all cases of analysed *t* values. Similarly, characteristic values $f_{ck(t)}$, calculated pursuant to Equation (5), meet the condition that at least 95% of samples of the analysed lot achieved such strength. Hence, characteristic values $f_{ck(t)}$ were defined, pursuant to Equation (5).

According to the Annex to Regulation no. 30 of GDDKiA of 16 June 2014, Table 9.4, for KR 7, the typical structure of the top layer of a rigid surface must have thickness of 29 cm (for core subgrade: mix with hydraulic binder C5/6, C8/10). According to Eurocode 2, for a (non-reinforced) C20/25 slab, which is 3x3 m and 30 cm thick, on C8/10 subgrade and with a load of 100 kN, the maximum strength totals 24 kNm/m, while cracking occurs at 30.9 kNm/m. Despite meeting the requirement for the cracking moment, in the RoadTronic solution, the slab features additional reinforcement at the top and at the bottom.

6. CONCULSIONS

The RoadTronic technology for constructing the top layers of rigid surfaces with mesh reinforcement envisages numerical control of an integrated assembly of robot machinery in charge of the following: intermediate storage of materials, placement of a reinforcement mesh of glass fibre rods at the bottom and at the top, component dosing, mixing, transport, extrusion grouting, and compaction of the concrete mix, with slab formation.

Owing to the precise operation of the robot, it is possible to apply the CSA-based concrete, which, after mixing with water, is characterized as follows:

- very short time to the onset of cement setting (approximately 0.2 to 0.5 h)
- then, immediate concrete hardening with rapid increments in its early strength, e.g., compressive strength f_{cm} - average test values were over 24 MPa, 31 MPa and 44 MPa, respectively, after 1.5 h, 4 h, and 168 h, while characteristic values f_{ck}(t), calculated according to the proposed equations totalled, respectively, 20.9 MPa, 25.2 MPa, and 39.3 MPa
- concrete slab achieving Condition I, permitting operational loads after 4 h, while, for Condition II, full bearing strength is achieved after 168 h

The characteristics of the RoadTronic technology include:

- predisposition for bus bay repairs during low-intensity traffic at night (between 18:00 and 02:00), so as to restore normal traffic at 06:00
- liberating workers of hard physical labour under difficult conditions
- controlling the execution of timely works for each concrete mix portion regarding the latest embedding time, by controlling preparation capacity, material embedding and the speed functions of the robot’s movements

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