Automation of the Execution of Monolithic Reinforced Ceilings

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Abstract

The development in numerical control, 3D technology, as well as new materials, have a great potential in respect of automatic construction, while at the same time they contribute to freeing people from hard physical labour, improve quality of performance, and minimise the volume of waste. Vertical components are erected automatically, while possible horizontal structures are engineered using prefabricated materials. The presented *stropotronic* technology, using automatic formwork that moves together with the robot embedding materials, was applied to construct monolithic reinforced ceilings. Owing to its high early strength (over 20 MPa just after 1.5 h from reaction with water), concrete using rapid setting calcium sulphoaluminate (CSA) cement assures self-supporting strength in a very short time. The robot continuously places reinforcement and extrudes concrete while moving together with the formwork perpendicularly to the ceiling span. Automatic formwork moves very slowly under the ceiling constructed to assure continuous support for the setting concrete at the width of approx. 1.5 m, namely until the slab becomes self-supportive across the span between supports. The example of a section of the ceiling with composite inserts (main bars of steel, distribution bars of glass fibre) presents the results of preliminary analysis of the applied CSA cement-based concrete, progress of works related to material embedding, and the conclusions.

Keywords –

automation in construction, production organization, JA-WA system, stropotronic, CSA cement

1 Introduction

Current automated construction systems using large-size 3D devices apply ‘wet’ technology with nozzles forming the material to build walls, whereas ceilings are assembled of prefabricated materials, [2, 3, 7, 11, 13, 22]. The *JA-WA* system (Polish: ***J**ednostronna **A**plikacja – **W**ędrującym **A**utomatem*) represents the technology of single-sided material application using mobile automatic devices, [14-16,18]. For construction of ceilings (Polish: *strop*), a prototype ‘*stropotronic*’ technology is proposed. The method allows construction of monolithic concrete ceilings reinforced with rods directly at the buildings constructed, with automated control of the equipment, according to a predefined numerical algorithm.

By standard, monolithic ceilings are placed on a prepared formwork placed in the space, relying on temporary supports, or on the floor. After stabilization of the formwork and placement of reinforcement inserts, the concrete mix is usually transported from the central concrete plant, and pumped at the site to the place of embedding, levelled, and mechanically compacted using manually operated power tools or manually. Following the period of concrete curing, the formwork can be removed, usually after several days, sometimes even later.

In the proposed *stropotronic* technology, ceiling construction is entirely different, and the time for supporting the formed part of the slab with the formwork totals just about 1.5 hours. The equipment is controlled by the operator, involving automatic formwork placement and a robot using the system for component mixing and embedding, according to the following principle. With the progress of works, automatic formwork and a robot placing reinforcement and coatings to secure against water evaporation and preparing the concrete mix for extrusion, as well as forming the external layers of the ceiling section, move on the rail scaffolding supported on the ground.

Precise operation of automatic equipment, appropriately to the results of analyses of the existing conditions and the calculation algorithm, with simultaneous continuous monitoring and control of the works quality, permits the application of rapid setting CSA (calcium sulphoaluminate) cement that takes about 30 minutes to begin, and with rapid early strength build-up. As a result, the support of the fresh ceiling with mobile formwork is only required for a short time, until the fresh concrete achieves the necessary strength to guarantee self-supporting properties of the executed section of the structure.

CSA cement, as applied in *stropotronic,* is a mineral, hydraulic binder with rapid early strength build-up (e.g. over 30 MPa after 8 from reaction with water), small contraction, and high resistance to sulphates. Main CSA components include: anhydrous *calcium sulphoaluminate* ($4CaO\ 3Al_2O_3 \cdot SO_4$), 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 *calcium sulphoaluminate*, gypsum, and i calcium hydroxide, involving dynamic heat generation and intense generation of ettringite, mineral that allows achieving high early strength, with full strength guaranteed by the manufacturer to be achieved after 3 - 7 days, [4, 5, 8-10, 21]. Due to immediate binding of such cement, it requires specialist (very efficient) execution.

2 *Stropotronic* technology for monolithic ceilings

The *stropotronic* kit includes:

- analytical algorithms for equipment control with monitoring of ambient conditions, [2, 14-16],
- the robot forming the ceiling, namely placing the reinforcement and protective coatings, as well as composing the components, and embedding the concrete mix,
- mobile formwork moving with the operating area, supporting the freshly made ceiling until it achieves self-supporting strength,
- scaffolding rail that supports the system equipment (mobile formwork and the robot) and transmitting load onto the ground, [14-16],
- intermediate material resource to assure logistic stock of materials to guarantee continuity of work, [12, 17, 19-20].

3 Analytical algorithms, robot forming the structure, and mobile formwork

During the works, appropriately to the changing conditions and rapid CSA cement-based concrete strength build-up, the control, monitoring, and quality control of the automatic mobile formwork, the robot embedding the materials, and the material stock are assured. Depending on the ambient thermal conditions and calculation results, the automatically controlled kit of equipment allows for real-time coordination, continuous preparation, and embedding of materials at strictly defined times, with the necessary production intensity. Keeping of the preparation and embedding times preconditions correct curing of the monolithic concrete structure, and the appropriate time of supporting the freshly made ceiling. Hence, the necessary efficiency of works execution and the equipment movement velocity are controlled.

According to Fig. 1, embedding kit A, executing ceiling 1, connected to mobile formwork B, continuously moves with the works section in direction 2.

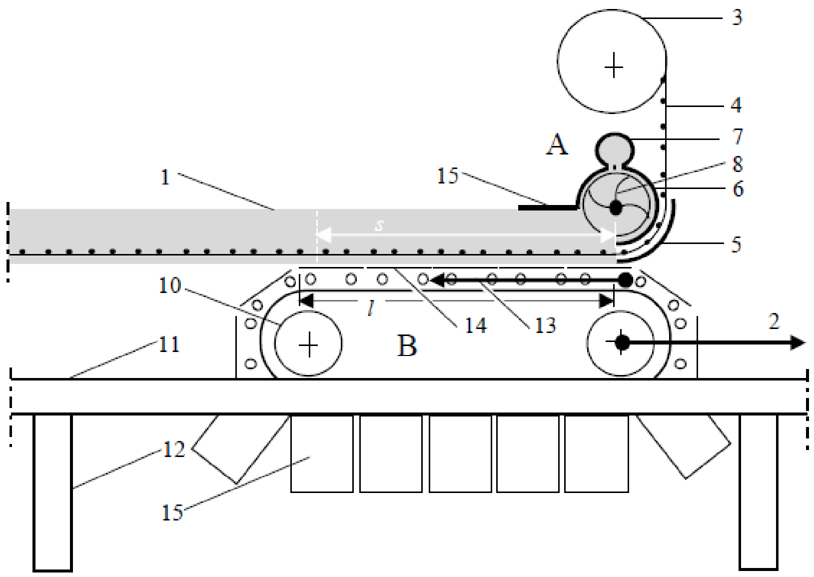

Figure 1. Diagram of the embedding kit - A and mobile formwork – B, description in the text

In the embedding kit A, the reinforcement mesh 4, unfolded from roll 3, for formed ceiling 1, is input between the front plate 5 and embedding kit casing 6. Concrete mix supplied with hose 7 is distributed across the ceiling span, extruded and compacted using carrier 8. Top plate 9 forms and smoothens outer surface of ceiling 1.

Mobile formwork B moves in direction 2 with the progress of the works, on wheels 10, on track 11, supported on supports 12. At the same time, particular formwork disks 14 move in the opposite direction 13. End parts of the formwork disks (over the tracks) are tilted. When the formwork plates move under, such end parts 15 on hinges tilt from the vertical, which allows for moving of formwork disks between the tracks and the supports.

The formwork supports freshly formed ceiling on section *l*, in the early period of (CSA cement-based) concrete curing for a time longer than until the fresh concrete achieves the parameters to guarantee its self-supporting properties in its entire cross-section at the span between the supports, as indicated below.

4 Properties of the applied CSA cement

During The first tests involving aluminous cement were conducted in the 1930's, including in France and in Poland by Stefan Bryła, [9, 10]. In 1966, in the USA, Alexander Klein proposed the application of calcium sulphoaluminate as the source of aluminium ions, and then patented the technology involving mixed Portland and expanding cements based on calcium sulphoaluminate, [1, 8-10,].

At present, CSA cement on calcium sulphoaluminates is 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 7 days). CSA cements stored in dry places in sealed packaging have the use by dates of 12 months. Major manufacturers of rapid setting cements are located in the USA and China. It is assumed that in the early period of CSA hydration, 80% ettringite is formed still before the hydration phase, and hence cement does not show strong expansion, and it can be classified as non-shrink cement. According to [19], after 28 days, in the conditions of very dry air, the contraction totals approx. 0.076 mm/m, while in the wet environment swelling of 0.2 mm/m occurs (acc. to ASTM C 845-96 [1], the limit for non-shrink cement totals up to 0.5 mm/m).

According to [4], CSA cement achieves compressive strength of f_{ck} = 20 MPa just one hour from its mixing with water, while after one day – 45 MPa, with full strength of 50 MPa, as guaranteed by the manufacturer, achieved after seven days. Later on, strength build-up occurs similarly as in Portland cements, and increases with time, totalling 62 MPa after 28 days. Further strength increase was investigated by Oreworld Cement Manufactured (OCM). As compared to compressive strength after 28 days, increase of 25% was recorded after one year, with further increase in strength of further 33% reported after five years [4].

Pursuant to the tests performed by the OCM, the proportions of tensile strength vs. compressive strength are similar as in Portland cements. Tensile strength after seven days totalled 4.1 MPa, with tensile strength at break of 5 MPa.

In order to achieve the intended strength parameters, CSA concrete preparation and laying must occur at outdoor temperature of from 7^{o}C to 32^{o}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 the temperature of 20^{o}C, according to [4], setting occurs just after 15 minutes or up to several minutes later. With citric acid used as a retardant, the onset of setting time can be elongated by 15 minutes.

The onset of CSA cement setting, usually occurring after just several minutes, requires non-standard execution of the works. The setting and curing processes occur almost immediately after the addition of water, much quicker than in the case of Portland cements. In most frequent cases, when performing urgent and short-lasting repairs, concrete teams trained and equipped with the suggested equipment perform works according to the predefined works organisation. Concrete must not be vibrated after it has started to set, and the surface must be secured against evaporation. During the work, tools must be systematically cleaned, usually not less frequently than every 30 minutes. Standard pumps and pipelines must also be cleaned at similar time intervals.

5 Concrete Mix tests

At the laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology in Krakow, preliminary compressive strength tests f_c, were performed on concrete on CSA Rapid Set® cement, with setting onset of t_{pw} = 32 minutes. Concrete Mix was applied available in 25 kg bags, [8]. The water, dry mix, and ambient temperatures totalled 20^{o}C. With water/cement proportion of w/c = 0.5, the test involved three cubic samples each, with dimensions of 100 x 100 x 100 mm, in each of 9 concrete age times, counting from the time of mixing with water. The results of the compressive strength tests performed according to EN 12390-1 [5] (on walter+bai ag DB 3000 press with control module NS19) have been presented in Table 1.

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

Test of concrete aged t, h	1.5	2	3	4	8	24	48	72	168
Average strength from tests $f_{cm(t)}$, MPa	24.9	27.3	29.9	31.5	35.1	37.9	40.2	41.5	44.3
Characteristic strength values, acc. to (1) $f_{ck(t)}$, MPa	20.9	23.3	25.9	27,5	31.1	33.9	36,2	37,5	39.3

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

When analysing the strength of samples tested (3 samples each, at 9 times, from 1.5 h up to 7 days; at the aforementioned laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology), major differences of the results, with standard deviation of s = 1.38, occurred for samples with concrete age of 8 h (from mixing the components with water). Average strength of three samples totalled $f_{cm(8)}$ = 35.1 MPa. *t*-Student was applied to check whether EN 1992:2008 Eurokod 2, [6], condition of 95 % samples in the lot achieving the characteristic strength, has been met. For sample strength of δ = 4 MPa lower than average $f_{cm(8h)}$, the value of test statistics $t_{obl} = (\delta/s)\sqrt{n-1}$, following substitution totals t_{obl} = 4.099 and is higher than *t*-Student distribution quantile of $t_{(0.95,\,2)}$ = 2.920. Therefore, the following was assumed that the characteristic concrete compressive strength $f_{ck(t)}$ at age t totals:

$$f_{ck(t)} = f_{cm(t)} - 4 \text{ MPa}, \quad \text{for } 1.5 \text{ h} \leq t \leq 168 \text{ h}, \qquad (1)$$

$f_{cm(t)}$ - average concrete compressive strength at the age of t hours.

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

According to Article [21], creep results of samples aged t_o = 1,5 h during the curing time of concrete CSA Rapid Set®, with the load of k_σ = 0,40, have indicated that deformations in creep-testing machines were lower than calculated according to EN 1992:2008 Eurokod 2, [6]. On day one, average sample deformation values in creep-testing machines totalled 0.74 deformation values calculated acc. to Eurocode 2, and the proportion decreased with time to 0.53 on the 7th day of the test.

6 The ceiling slab structure

It was assumed that the analysed ceiling slab is unfinished, free-supported at the edges, made of reinforced concrete. Main reinforcement is made of A-III ribbed steel, and distribution bars - of glass fibre composite rods. The solution allows rolling a long section of the prefabricated mesh (owing to its high elasticity and shape memory of the composite rods as distribution rods).

Three phases have been defined in the behaviour of the load-bearing structure. State I, or self-supporting ceiling slab (without an external load), state II – planned layers in the ceiling, and state III – corresponding to target behaviour of the load-bearing structure with full operational load.

6.1 State I – self-supporting ceiling slab

According to the tests, CSA-based concrete of age t = 1,5 h (from mixing with water) was characterised with strength $f_{cm(1.5)}$ = 24.9 MPa, cf. Table 1. After calculation acc. to equation (1), characteristic strength totalled $f_{ck(1.5)}$ = 20.9 MPa.

Pursuant to calculations according to EN 1992:2008 Eurocode 2 for unfinished slab, free-supported at the edges, with axial distance between supports of 3.3 m, thickness of 0.15 m, loaded with own weight q = 3.6 kN/m^2, for concrete C 16/20, with agglomerate of 0.8 cm, with cover of 1.5 cm (C_{dev} = 1.0 cm, C_{dur} = 0.0 cm), and reinforcement of A-IIIN grade ribbed steel (RB500), with calculated elasticity limit of f_{yd} = 435 MPa:

- reinforcement cross section area:

$$A_{s1I} = 2.01 \text{ cm}^2.$$

- bend deflection:

$$f_I = 0.07 \text{ cm}.$$

The following was assumed:

- main reinforcement φ = 0,8 cm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm^2.

6.2 State II of planned layers in the ceiling

In the above conditions, pursuant to laboratory tests and calculations according to (1), it was assumed that CSA-based concrete with age t = 24 h has characteristic strength of $f_{ck(24)}$ = 33.9 MPa. For C 25/30 concrete grade, with constant load q = 5.1 kN/m^2:

$$A_{s1II} = 2.01 \text{ cm}^2, \quad f_{II} = 0.11 \text{ cm}.$$

Therefore, reinforcement as in section 6.1, namely φ = 8 mm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm^2 , are bigger than required for state II.

6.3 State III of slab bearing strength with operational loads

In the conditions as in section 6.1, it was assumed that CSA-based concrete with age t = 168 h has characteristic strength of $f_{ck(168)}$ = 39.3 MPa. For C 30/37 concrete grade, with constant load of 5.6 kN/m^2 and variable load of 2.0 kN/m^2:

$$A_{s1\text{III}} = 4.81\ \text{cm}^2,\ f_{\text{III}} = 1.00\ \text{cm},$$

$$f_{\text{I}} + f_{\text{II}} + f_{\text{III}} = 1.18\ \text{cm} < f_{\max} = 1.32\ \text{cm}.$$

Therefore, the applied reinforcement as in section 6.1, namely φ = 0.8 cm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm^2, are bigger than required for state III with target load, and the final slab deflection is lower than permissible.

7 Time limits for concrete mix embedding

In the *stropotronic* technology, automatic mixing of components with water, and their direct transport and dynamic extrusion embedding (mechanical compacting of the concrete mix with pressure exerted by the carrier blades) occurs in one continuous production process. Any portion of the mix that has water added into it at a specific moment features two important process times to be noted. One, 'the latest time' after which no vibrations from the dynamic extrusion of fresh material embedded can affect the cement during its setting time, and the other, 'the earliest time' to assure that the time of supporting the freshly formed section of the ceiling has been long enough, and concrete age assures the necessary compressive strength and the structure can start functioning as a self-supporting structure from that time onwards.

7.1 The latest time of concrete mix embedding

According to the conditions of correct workmanship, after t_{pw} – onset of cement setting, the concrete mix must not be moved or exposed to vibrations, initiated here by the machine upon material compaction, as this might cause damage to the bonding crystals formed. Therefore, it must be assured that the formed mix is no longer exposed to vibrations transferred by the material laid from the added and mechanically compacted mix still before the onset of CSA cement setting. Because of intense attenuation occurring in the pressure-densified fresh mix in our solution, the vibration zone is small, and already at a small distance a, totalling up to a few cm from the surface of direct exposure to compacting machine blades, the harmful impact is limited.

Therefore, in reference to each portion of the mix, at a time shorter than until the onset of CSA cement setting, components must be mixed with water, transported, and embedded, with such a quantity of material added so that the operating zone of the machine is moved away to the distance a, in order to eliminate the negative impact of vibrations. This can be written as:

$$t_{pw} \geq t_m + t_{tw} + t_a \tag{2}$$

t_{pw} – time interval from mixing components with water until the onset of CSA cement setting time, t_{pw} = 32 minutes,

for concrete mix portion (mixed with water at time t) duration:

t_m – component mixing, t_m = 2 minutes,

t_{tw} – transport and extrusion (in the most unfavourable case, with mix transport to the most remote embedding location, namely at the section of 3 m) t_{tw} = 9 minutes,

t_a – construction of a ceiling section with length a = 8 cm, in minutes.

After transforming the equation (2) and substitution of values, the construction time of section a = 8 cm of the ceiling must meet the following condition: $t_a \leq$ 21 min.

7.2 The earliest time of formwork removal

Automatic machine forms the ceiling section on consecutive mobile formwork discs that move underneath, continuously under the freshly placed concrete mix, cf. Fig. 1. Characteristic compressive strength $f_{ck(t)}$, as above, depends on age t – of the analysed portion of concrete. According to section 6.1, a slab of reinforced concrete automatically formed on formwork discs achieves self-support function in the span between the supports, namely state I, at the age of CSA-based concrete totalling t_{I}. Therefore, the earliest time of removing the formwork supporting the ceiling in the span between the supports corresponds to the age of concrete totalling t_{I}. When analysing the embedding process, one can write it as:

$$t_{\text{I}} \geq t_m + t_s \tag{3}$$

t_{I} – age of concrete upon the ceiling slab becoming self-supportive (without an external load) in the span between supports – state I, t_{I} = 90 minutes,

t_m – as above, component mixing time (t_m = 2 minutes; here, during the mixing, the material is transported to the nearest place of embedding; hence, the time t_{tw} – transport and extrusion was omitted)

t_s – applicable period of supporting the ceiling slab in the span between the supports with mobile formwork, in minutes.

After transformation of equation (2), the applicable period of supporting a ceiling slab section in the span between the supports with the mobile formwork (corresponding to the earliest time of the ceiling becoming self-supportive in the span between the supports) can be specified with the equation:

$$t_s \geq t_I - t_m. \tag{4}$$

Due to the short time of component mixing t_m, the assumption is that $t_s \geq t_I$.

7.3 Maximum speed of machine and mobile formwork movement

The automatic machine moves in the time t_s (namely period where concrete achieves the strength to assure self-supportive ceiling in the span between the supports) at the section with the length of:

$$s = vt_s \tag{5}$$

v – ceiling construction speed, corresponding to the moving speed of the automatic machine, cm/min.

In order to meet the condition of ceiling support in the span between the supports for the applicable time interval t_s, it is required that l – the width of formwork discs supporting the curing concrete (cf. Fig. 1) is not lower than s – length of the ceiling section constructed in such time interval t_s, hence:

$$l \geq s. \tag{6}$$

In equation (5), following the substitution for s and transformation, velocity v of machine movement when constructing the ceiling must meet the following condition:

$$v \leq l/t_s\,. \tag{7}$$

In the case analysed, when freshly constructed ceiling is supported by formwork discs at the section l = 1.5 m, and with value t_s = 1.5 h, the moving speed of the machine is low, and totals $v \leq 1.0$ m/h (namely $v \leq 1.67$ cm/min).

Similarly, efficiency Q of embedding concrete mix in m^3/h can be calculated using the equation:

$$Q \leq hbv, \tag{8}$$

h and b – respectively, thickness and width (span) of the ceiling section constructed, m.

In the case of a ceiling with slab thickness of h = 0.15 m, span b = 3.3 m and machine and formwork movement velocity as above, $v \leq 1$ m/h, concrete mix embedding efficiency totals $Q \leq 0.45$ m^3/h (namely 7.52 dcm^3/min).

8 Conclusion

The prototype *stropotronic* technology for construction of monolithic concrete ceilings with mesh reinforcement:

- envisages numerical control of an integrated sequence of machinery in charge of: intermediate material stock – dosing, mixing, and transport of components – placement of reinforcement and extrusion of the concrete mix – support of the formed structure during concrete curing for the required period of time;
- applies the system for material preparation and feed, including a robot embedding the reinforcement mesh of main steel rods and distribution rods of glass fibre, as well as concrete mix on rapid setting CSA cement, as well as simultaneously moving mobile formwork to support the constructed structure during concrete curing time, until the ceiling slab achieves self-supporting properties (across the span between the supports; after the formwork has been removed from the ceiling constructed, the self-supporting slab must not be exposed to external loads for 24 hours).

  Owing to numerical control, and as a result of precise operation of the robot embedding the materials, and mobile formwork, it is possible to apply the CSA (calcium sulphoaluminate) cement-based concrete which, after mixing with water, is characterised with:
- very short time to the onset of cement setting (approximately 0.2 to 0.5 h);
- next, immediate concrete hardening and rapid increment in its early strength, e.g. compressive strength f_{cm} – average test values were over 24 MPa, 37 MPa, and 44 MPa, respectively after 1.5 h, 24 h, and 168 h, while characteristic values $f_{ck(t)}$ calculated according to the proposed equations totalled, respectively 20.9 MPa, 33.9 MPa, and 39.3 MPa;
- ceiling slab made as above achieves state I of self-support (across the span between the supports) after 1.5 h, state II allowing for execution of planned layers in the ceiling – after 24 hours, while state III of complete load bearing capacity adjusted to target loads is achieved after 168 hours.

  According to the calculation algorithm, the conditions of timely works execution in respect of each concrete mix portion are continuously controlled in the aspect of:
- the latest embedding time,
- the earliest formwork removal time,
- through control of material preparation and embedding efficiency, as well as robot and mobile formwork moving speed.

Characteristics of *stropotronic* technology include:

- liberating people of hard physical labour, including the need to prepare labour-intensive formwork in difficult site conditions;
- adjustment of the equipment and progress of works to the properties of materials applied; here: rods of glass fibre and CSA cement;
- limited involvement of technical means, namely low weight and low capital intensity of the solution.

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