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**Research paper**

# Correct concrete load-bearing capacity and time limitations for the automatic implementation of monolithic reinforced ceilings

**A. Więckowski**[1]

**Abstract:** Digital control, 3D technique and new materials show great potential in the automation of construction processes. Simultaneously releasing humans from hard physical labour come improvements of quality of workmanship and better resource and time management. In normal construction, vertical elements are erected robotically and horizontal (ceiling) elements are prefabricated. The "Stroptronic" technology presented here, tries to improve on that, introducing a "Just In Time" sequence of events on-site. The robot arranges all materials into a cycle and forms a monolithic, reinforced ceiling slab, sliding on a conveyor and rollers during the primary bonding of concrete. The concrete, based on a quick-setting cement composed with calcium sulfo-aluminate (CSA); ensures the ceiling early self-bearing capacity thanks to its high early strength (over 20 MPa, 1.5 hours after mixing). The robot constantly introduces reinforcements, prepares and extrudes the concrete mix, moving in a direction perpendicular to the ceiling span. Along with the robot, the conveyor and the rollers move slowly under the ceiling, providing continuous support to the bonding concrete over a distance of about 1 m, i.e. until it reaches self-bearing capacity in the cross-section between the supports. Tests of the concrete with CSA are hereby produced, progress in bonding materials is analysed, along with results of testing load-bearing capacity of a section with composite inserts (main bars – steel, distribution bars – fibreglass. Results and conclusions follow.

**Keywords:** automation of construction, *Stroptronic*, CSA cement

[1] Assoc. Eng. prof. AGH, AGH University of Science and Technology, Faculty of Mining and Geoengineering, Department of Geomechanics, Civil Engineering and Geotechnics, Al. A. Mickiewicza 30, 30-059 Cracow, Poland, e-mail: awiecko@agh,edu.pl

# 1. Introduction

Examples of fully automated robots for erecting multi-storey buildings include: AMURAD (AutoMatic Up-Rising Construction by ADvance Technique, [2]) SMART System (Shimuzu Corporation, [10, 14]) ABSC (Automated Building System Construction, [2]). Construction development concept of erecting buildings and their entire complexes is addressed by CC (Contour Crafting, [1, 6]). The CC uses an arranging-forming device and, as in other systems, prefabricated ceilings. All these solutions require creation of mobile, automatic factories capable of production at the construction site. Resulting equipment then, is very heavy, weighing several hundred tons and more. It is also very capital intensive.

The JA-WA system (in Polish: Jednostronna Aplikacja – Wędrującym Automatem) represents the technology of single-sided material application using mobile automatic devices [16]. The author's prototype "Stroptronic" technology is proposed [15] for the construction of ceilings. This technology uses a digital algorithm, enabling the production of an 'instant", monolithic, reinforced concrete ceiling, constructed "just in time" to be placed directly on the building being erected, in a single pass of the automatic stacker. The execution of the ceiling is completely different,. The time of supporting the newly formed strand by the conveyor and the rollers of the stacker (i.e. until the ceiling in the supported cross-section becomes set), is measured in minutes. Continuous monitoring and ongoing control of performance, allow the use of CSA (sulphate-clay-calcium) cements with shortest bonding periods, and very fast increase in early strength [8, 9, 18].

CSA cements are usually used for necessary express renovations, e.g. repairs of heavily used town squares, bus/trams stops, road surfaces and runways of airports, as well as for fragments of hydro and mining facilities, bridges and viaducts. CSA cement was used during the urgent reconstruction of the US Department of Defence building (after the September 11, 2001 attack). It was also used in the renovation of Runway 16C at Seattle-Tacoma airport, originally built in 1969 [13]. In the years 1994–2005, 531 damaged slabs were removed from the original 1748 (6m x 6m) concrete slabs. They have been replaced by new slabs using CSA cement (about 30,000 $m^3$). The work schedule read as follows: Runway closed to plane traffic at 11PM, concrete works completed at 3AM and the first plane landed on the new surface at 6.30 AM. Detailed tests were carried out in 2012. It was found that after 7–18 years of operation, the failure rate of concrete slabs with cement CSA amounted only to 3.8% – several times lower than the failure rate of original slabs made using Portland cement.

A new proprietary version of the Stroptronic machine is presented below. It supports the freshly formed band of ceiling on a conveyor and rollers (in the article [15] and according to the patent [11], the ceiling slab is formed on shields, supporting the entire surface, which move in the opposite direction to the machine producing the ceiling). Current tests performed on fifteen concrete age samples determined the variability functions of compressive strength of young concrete in relation to time t (measured from mixing of components with water until the destructive tests). Functional dependencies of strength for two concrete age ranges are determined to be: 0.7 h $\leq t \leq$ 1.5 h and 1.5 h $\leq t \leq$ 168 h. Then, 4 significant states of endurance are examined: State I - Self-bearing shown by the ceiling band between the supporting elements of the automatic stacker. State II – Self-bearing of the ceiling band between permanent supports (e.g. load-bearing walls). State III Capacity for supporting extra layers added to the ceiling. State IV – Full load-bearing capacity as experienced by the element. Analyzing above data, the minimum and maximum speeds for robotic execution of the ceiling slab, were defined. The strength test of a ceiling fragment, built on a prototype Stroptronic machine in the laboratory of the Department of Geomechanics, Construction and Geotechnics of AGH, is then presented along with conclusions.

## 2. Construction of monolithic ceilings in Stroptronic technology

Stroptronic technology consists of: analytical algorithms for device control along with monitoring of ambient conditions [15, 17] and an automatic stacker forming the ceiling band.

The ceiling in the Stroptronic technology, is supported on walls and / or load-bearing beams, at the destined location, and produced as a fixed, monolithic, reinforced concrete slab.

According to Fig. 1, the automatic stacker A, forming ceiling 1, moves in the $v$ direction.

The mobile automatic stacker A, as work progresses, moves in the direction $v$, on wheels 3, along track 2 supported by the ground or the floor of the lower storey, [11].

In the stacker device A, the lower reinforcement mesh 5, served from a roll 4 and the lower membrane served from roll 6, into the forming ceiling 1, are inserted between the front plate 8 and the stacker conveyor housing 9. Between the top forming surface and smoothing plate 10 and the stacker housing 9, is introduced upper membrane 11 served from the roll 12 (and possibly the upper reinforcement mesh). Ingredients are supplied from the outside by the dispenser 20 and metered into the mixer 21. The prepared concrete mix is moved by element 22 to the conveyor 13, which distributes it over the entire width of the strand and extrudes it to the full height h of ceiling 1. The slide plate for freshly made the band of ceiling is a continuous support on the section $s_1$ (up to several dozen cm in length).

A conveyor 13 forms a band of ceiling, in the cross section $\varphi_o$ on the slide plate 15. Further, support rollers of the band of ceiling, already occur at intervals (amounting to over a dozen to several dozen cm). The distance $s_2$ from the edge 16 of the slide plate to the first support roller 17 and the next distance $s_k$ to the roller 18 etc. until the distance $s_n$ to the support last roller 19. Afterwards, the ceiling band no longer needs support from the elements of the automatic stacker and maintains stability in cross-section between the target supports, e.g. between load-bearing structural walls.

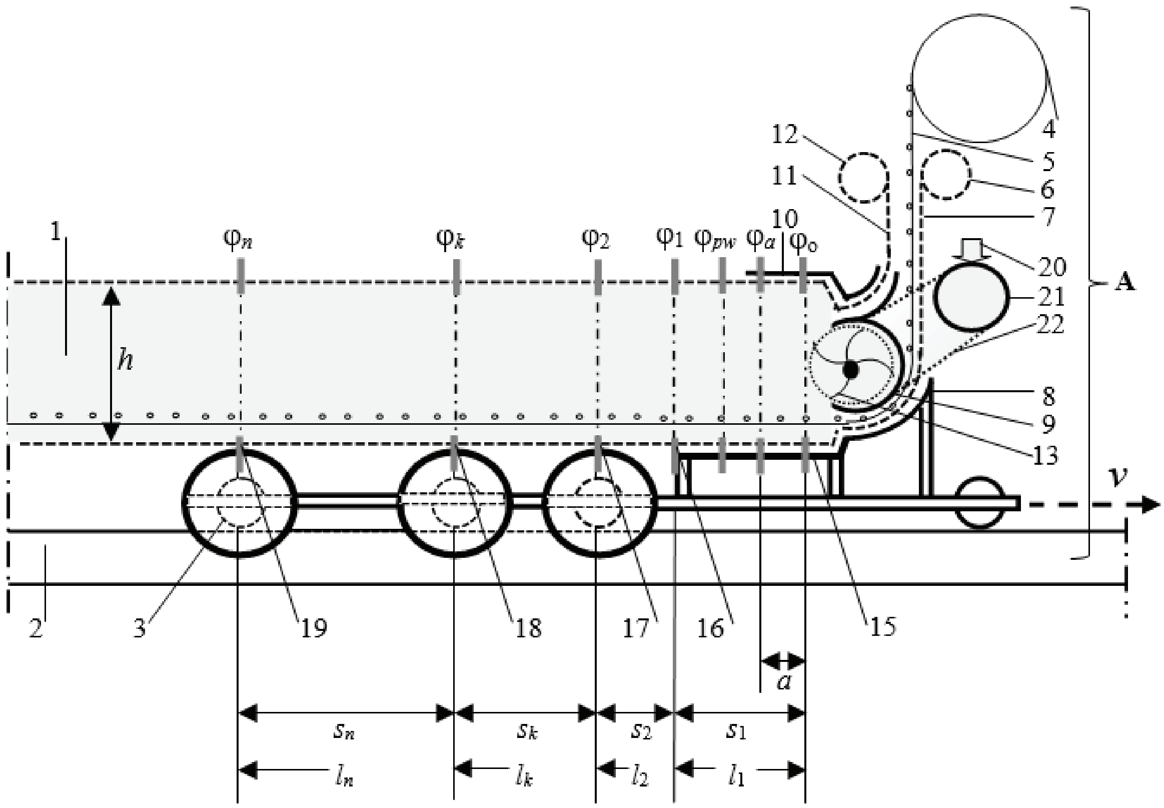


Fig. 1. Diagram of the automatic stacker assembly – A, description in the text [sketch by the author]

## 3. Compressive strength of CSA – based concrete

Preliminary tests were carried out, (in the laboratory of the Faculty of Geomechanics, Construction and Geotechnics of the AGH University of Science and Technology in Cracow), of $f_c$ compressive strength of Rapid Set® concrete based on CSA cement, with the beginning bond at $t_{pw}$ = 32 minutes. A concrete mix used, came from Korodur in 25 kg bags, [3, 7]. The temperature of the water, dry mix and the environment was the ambiant 20°C. The water to cement ratio of $w/c$ = 0.5. “Age of concrete” was determined from the moment of adding water to the cement until testing. The test was repeated with each of the 15 samples of the concrete age. For each age of concrete, 3 cubic samples of 100×100×100 mm were tested. The compressive strength tests were carried out, in accordance with EN 12390-1, [4] (in destructive tests on the walter + bai ag DB 3000 press, with the NS19 control module) and obtained results are presented in Table 1 and Fig. 2.

Concrete strength over time, among other considerations, depends on the type of cement, temperature and care conditions. According to EC2 [5], more accurate values, especially at $t \leq 3$ days, should be determined on the basis of tests.

With the Stroptronic technology using CSA cements and immediate removal of support from the young concrete band, it is necessary to know the compressive strength $f_{ck(t)}$, already at the age of concrete $t \geq 0.7$ h.

Table 1. Variability in the time of the Rapid Set® concrete compressive strength on CSA cement [the author's own study]

| Age concrete, $t$, h | 0,6 | 0,7 | 0,8 | 0,9 | 1 | 1,25 | 1,5 | 2 | 3 | 4 | 8 | 24 | 48 | 72 | 168 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average strength from tests, $f_{cm}$, MPa | 0,38 | 2,71 | 6,24 | 8,95 | 10,2 | 15,6 | 24,9 | 27,3 | 29,9 | 31,5 | 35,1 | 37,9 | 40,2 | 41,5 | 44,3 |
| Standard deviation, $s$ | 0,42 | 0,29 | 0,60 | 0,69 | 0,17 | 0,71 | 0,56 | 0,43 | 0,94 | 1,13 | 1,38 | 0,15 | 0,88 | 1,09 | 1,21 |

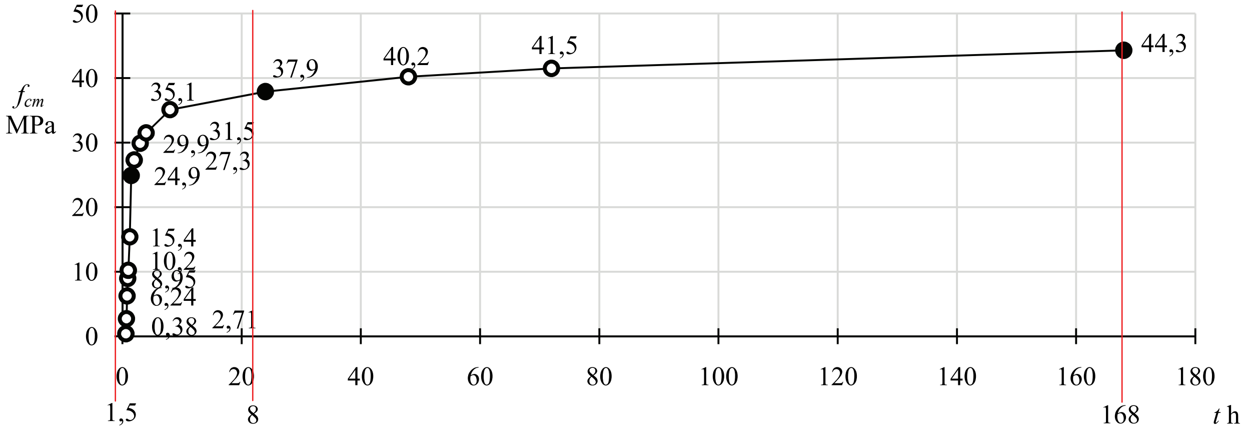


Fig. 2. Compressive strength $f_{cm}$ of Rapid Set® samples on CSA cement due to the age of concrete $t$ [the author's own study]

Analysing the results of tests on the compressive strength of samples in 15 cases of the age of concrete, from 42 minutes to 7 days, two ranges of results variability are distinguished. Based on the results of the tests according to Table 1, the functions $f_{cm(t)}$ of the average compressive strength of concrete with CSA cement are determined below, depending on the age of concrete $t$, for two separate time intervals, in accordance with the relations:

$$f_{cm(t)}^{\text{CSA}} = 30 \cdot f_{cm(168)} \cdot \exp(-(0{,}1\,\alpha_{(t)})^{0{,}575}), \quad \text{for } 0.7 \text{ h} \leq t < 1.5 \text{ h}, \tag{3.1}$$

(3.2) $$f_{cm(t)}^{\mathrm{CSA}} = 2{,}7 \cdot f_{cm(168)} \cdot \exp(-(\alpha_{(t)})^{0{,}06}) \cdot (\alpha_{(t)})^{-0{,}052}, \text{ for } 1.5\text{ h} \le t \le 168\text{ h},$$

$f_{cm(t)}^{\mathrm{CSA}}$ – average compressive strength of the age of concrete $t$ h (hours),

$f_{cm(168)}$ – average compressive strength of concrete at 168 h (7 days),

$\alpha_{(t)}$ – coefficient depending on the age of the concrete, $\alpha_{(t)} = 168/t$ ($t$ – the age of the concrete calculated from the time the cement is mixed with water, in h).

In the age range of 0.7 h $\le t \le$ 1.5 h samples tested at six intervals, the largest spread of strength results with standard deviation $s_{1,25}$ = 0.71 took place in samples of concrete age $t_{1.25}$ = 1,25 h and medium strength $f_{cm1,25}$ = 15,6 MPa, while in the age range 1.5 h $\le t \le$ 168 h the largest discrepancy of results, with a standard deviation $s_8$ = 1.38 took place with samples of concrete age $t_8$ = 8 h and average strength $f_{cm8}$ = 31.5 MPa.
Compliance with the EC2 condition [5], that 95% of the samples of the tested batch achieved the characteristic strength, was checked by the Student's $t$-test. For the strength of samples less by $\delta_{1,25}$ = 1.5 MPa than the average $f_{cm(1,25\mathrm{h})}$ = 15.6 MPa, the value of the test statistics $t_{\mathrm{obl}} = (\delta / s)\sqrt{n-1}$ after substitution is $t_{\mathrm{obl}1,25}$ = 2.988 and is greater than the quantile of the $t$-distribution Student equal $t_{(0{,}95,\,2)}$ = 2.920. Thus, it was adopted:

(3.3) $$f_{ck(t)}^{\mathrm{CSA}} = f_{cm(t)}^{\mathrm{CSA}} - 1.5\text{ MPa, for } 0.7\text{ h} \le t < 1.5\text{ h.}$$

Similarly as above, analysing the strength of tested samples (from 9 dates, between 1.5 hours to 7 days) the largest spread of results took place for samples with a concrete age of 8 h. For samples with strength lower by $\delta_8$ = 4 MPa from the average $f_{cm8}$ = 31.5 MPa, the value of statistics is $t_{\mathrm{obl}8}$ = 4.099 is greater than the quantile of the Student's $t$ distribution equal to $t_{(0{,}95,\,2)}$ = 2.920. Thus, it was adopted:

(3.4) $$f_{ck(t)}^{\mathrm{CSA}} = f_{cm(t)}^{\mathrm{CSA}} - 4\text{ MPa, dla } 1{,}5\text{ h} \le t \le 168\text{ h.}$$

Tables 2 and 3 as well as Fig. 3 and 4 show the CSA strength of young concrete found in the tests and calculated on the basis of the relationships (3.1) and (3.3) as well as (3.2) and (3.4), respectively.

Table 2. Rapid Set® concrete strengths at the age of 0.7 h ≤ $t$ <1.5 h based on tests and calculated according to the relationship (3.1) and (3.3) [the author's own study]

| Age concrete, $t$ h | 0,7 | 0,8 | 0,9 | 1 | 1,25 | 1,5 |
|---|---|---|---|---|---|---|
| Average strength from tests, $f_{cm}$, MPa | 2,71 | 6,24 | 8,95 | 10,2 | 15,6 | 24,9 |
| Average strength, acc. to (3.1), $f_{cm(\mathrm{t})}$, MPa | 2,65 | 4,20 | 6,12 | 8,39 | 15,45 | 24,06 |
| Characteristic strength values, acc. to (3.3), $f_{ck(\mathrm{t})}$, MPa | 1,15 | 2,70 | 4,62 | 6,89 | 13,95 | 22,56 |

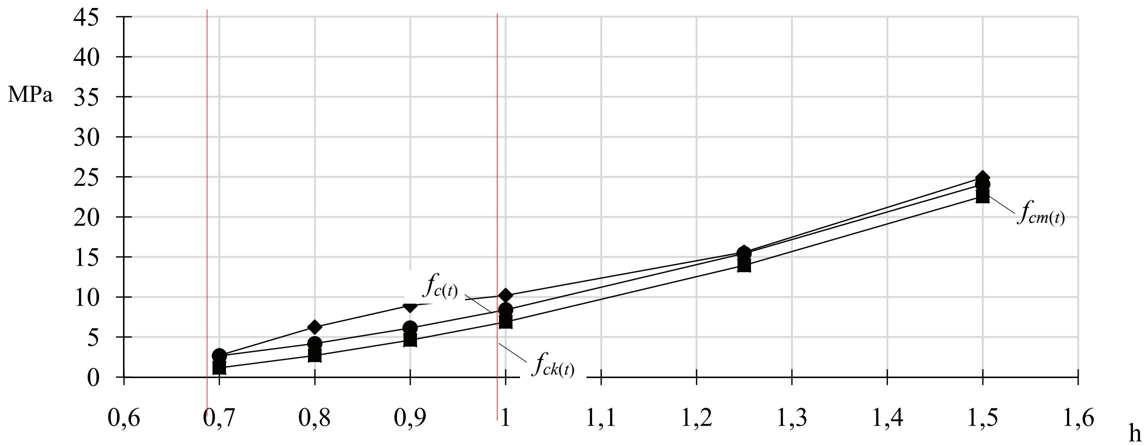


Fig. 3. Strengths of young Rapid Set® concrete at the age of 0.7 h ≤ $t$ <1.5 h: $f_{cm}$ - average values based on tests and $f_{cm(\mathrm{t})}$ and $f_{ck(\mathrm{t})}$ - calculated according to the relationship (3.1) and (3.3) respectively [the author's own study]

Table 3. Rapid Set® concrete strengths at the age of 1.5 h ≤ $t$ <168 h based on tests and calculated according to the relationship (3.2) and (3.4) [the author's own study.

| Age concrete, $t$ 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, acc. to (3.2), $f_{cm(\mathrm{t})}$, MPa | 24,82 | 25,77 | 27,16 | 28,18 | 30,74 | 35,14 | 38,13 | 39,97 | 44,00 |
| Characteristic strength values, acc. to (3.4), $f_{ck(\mathrm{t})}$, MPa | 20,82 | 21,77 | 23,16 | 24,18 | 26,74 | 31,14 | 34,13 | 35,97 | 40,00 |

According to Tables 2 and 3 and Fig. 3 and Fig. 4, the average compressive strength $f_{cm(\mathrm{t})}$ calculated on the basis of the relationship (3.1) and (3.3) is smaller than the strength of the tested samples $f_{c(t)}$ in all cases of the analysed values of $t$. Similarly, the characteristic strength $f_{ck(\mathrm{t})}$ calculated according to the relationship (3.2) and (3.4) meets the condition that at least 95% of the samples of the tested batch achieve such strength. Hence, further characteristic strength $f_{ck(\mathrm{t})}$ was determined according to the relations (3.2) and (3.4).

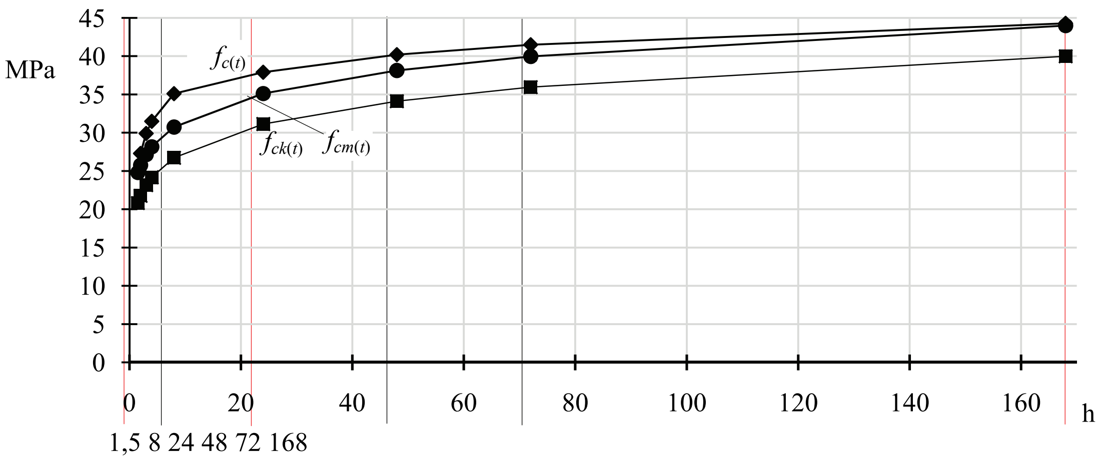


Fig. 4. Strengths of young Rapid Set® concrete at the age of 1.5 h ≤ $t$ <168 h: $f_{cm}$ – average values based on tests and $f_{cm(\mathrm{t})}$ and $f_{ck(\mathrm{t})}$ – calculated according to the relationship (3.2) and (3.4) respectively [the author's own study]

# 4. Load capacity in cross sections of the ceiling band

Four strength states were distinguished in the construction of the ceiling. Stage I – condition of self-supporting of the ceiling slab between supporting elements in the automatic stacker. State II – Self-bearing of the ceiling band between permanent supports (e.g.the load-bearing walls). State III Support capacity for extra layers added to the ceiling. State IV – Full load-bearing capacity as experienced by the element.

## 4.1. Condition of self-bearing of the ceiling slab between supporting elements in the automatic stacker – state I

In the State I condition, it was assumed that that in every cross section $\varphi_i$, $i = 1, \ldots, n - 1$, over the supporting elements in the automatic stacker,, the strength of the young concrete is sufficient to ensure the self-bearing capacity of the ceiling with a span of $s_{i+1}$, i.e. to the adjacent support in the cross section $\varphi_{i+1}$.

Calculations were based on the assumption that the analysed slab is 0.15 m thick and with a span of $s_{i+1}$ corresponding to the distance between the cross sections $\varphi_i$ and $\varphi_{i+1}$ above the adjacent supports of the stacker.

### 4.1.1. The first freely supported section of the ceiling

A span of the first freely supported section of the ceiling $s_2$ = 0.2 m was assumed, i.e. from the cross-section $\varphi_1$ over the edge 16 of the conveyor to the cross-section $\varphi_2$ over the first support roller 17 (comp. Fig. 1). Table 4 shows calculations assuming a slab of 0.15 m thickness and 1 m width.

Table 4. Calculations for the analyzed sections of floor slabs with a spans of 0.2 m and 0.35 m

| | | | | |
|---|---|---|---|---|
| Weight, kN/m | $q$ | 5,1 | $b \cdot h \cdot \rho \cdot \gamma_G$ | $0{,}15 \cdot 1 \cdot 25 \cdot 1{,}35$ |
| Moment zginający, kNm | $M_{0,2}$ | 0,025 | $ql^2/8$ | $5{,}1 \cdot 0{,}2^2 \cdot 0{,}125$ |
| | $M_{0,35}$ | 0,078 | | $5{,}1 \cdot 0{,}35^2 \cdot 0{,}125$ |
| Bending moment, $m^3$ | $W_{x0,2}$ | 0,00375 | $bh^2/6$ | $1{,}0 \cdot 0{,}15^2/6$ |
| | $W_{x0,35}$ | | | |
| Tensile stress, $kN/m^2$ | $\sigma_{ctr0,2}$ | 6,67 | $M/W_x$ | 0,025/0,00375 |
| | $\sigma_{ctr0,35}$ | 20,83 | | 0,078/0,00375 |
| Characteristic concrete strength to compression, MPa | $f_{ck(0,7h)}$ | 1,15 | By relationship (3.3) | Table 2 |
| | $f_{ck(1h)}$ | 6,89 | By relationship (3.4) | Table 3 |
| Tensile strength[1], MPa | $f_{ctm(0,7h)}$ | 0,33 | $0{,}3 \cdot f_{ck}$^(2/3) | $0{,}3 \cdot 1{,}15^{(2/3)}$ |
| | $f_{ctm(1h)}$ | 1,09 | | $0{,}3 \cdot 6{,}89^{(2/3)}$ |
| Characteristic concrete axial tensile strength, MPa | $f_{ctk,0,05(0,7h)}$ | 0,21 | $0{,}7 \cdot f_{ctm}$ | $0{,}7 \cdot 0{,}33$ |
| | $f_{ctk,0,05(1h)}$ | 0,76 | | $0{,}7 \cdot 1{,}09$ |
| Computational axial tensile strength of concrete, $kN/m^2$ | $f_{ctd(0,7h)}$ | 140 | $f_{ctk,0,05}/\gamma_c$ | 0,21/1,5 |
| | $f_{ctd(1h)}$ | 507 | | 0,76/1,5 |

[1] Acc. PN-EN 206+A1:2016-12, [12]

The young concrete based on CSA cement, with an age of $t_{0,7}$ = 0.7 h, with characteristic compressive strength, as above $f_{ck(0,7h)}$ = 1.15 MPa, meets the standard requirements, as per calculations in table 4, according to the following relationship:

$$f_{ctd(0,7h)} = 140\ \text{kN/m}^2 > \sigma_{ctr0,2} = 6{,}67\ \text{kN/m}^2.$$

### 4.1.2. Another freely supported section of the ceiling

Next considered is the span of another freely supported section of the ceiling, in this case $s_3$ = 0.35 m, i.e. from the cross-section $\varphi_2$ above the support roller 17 to the cross-section $\varphi_3$ above the next adjacent support roller 18. Calculations with above conditions are presented in Table 4. The results obtained, for young concrete with an age of $t$ = 1 h, with a characteristic compressive strength of $f_{ck(1h)}$ = 6.89 MPa confirm compliance to the standard, according to the relation:

$$f_{ctd(1h)} = 507\ \text{kN/m}^2 > \sigma_{ctr0,35} = 20{,}83\ \text{kN/m}^2.$$

Thus, with supports at distances $s_2$ = 0.2 m and $s_3$ = 0.35 m, the formed band of ceiling in the analysed cross-sections $\varphi_1$ and $\varphi$ achieves strengths $f_{ctd(0,7h)}$ and $f_{ctd(1h)}$, meeting the requirements of the standard.

### 4.2. Ceiling load-bearing capacity in states II–IV

Based on calculations according to Eurocode 2 [5], for an infinite slab, free-supported at the edges with an axial spacing of 3.3 m, 15 cm thick, of concrete with 8 mm aggregate and a 1.5 cm cover ($C_{dev}$ = 1.0 cm, $C_{dur}$ = 0.0 cm), reinforced with A-IIIN (RB500) ribbed steel with a yield strength of $f_{yd}$ = 435 MPa, loaded with:

- own weight $q$ = 3.6 kN / m$^2$, state II,
- own weight $q$ = 5.1 kN / m$^2$, state III,
- own weight $q$ = 5.1 kN / m$^2$, variable $q_k$ = 2.0 kN/m$^2$, state IV,

the results of the calculations are summarized in Table 5.

Table 5. Results of ceiling load capacity calculations in states II–IV

| | | | State II | State III | State IV |
|---|---|---|---|---|---|
| Age concrete | | h | 1.5 | 24 | 168 |
| Load | Constant | kN/m$^2$ | 3.6 | 5.1 | 5.6 |
| | Variables | kN/m$^2$ | – | – | 2.0 |
| Characteristic concrete strength to compression, occ. (3.4), table 3 | | MPa | $f_{ck(1,5)}$ = 20.82 | $f_{ck(24h)}$ = 31.14 | $f_{ck(168h)}$ = 40.00 |
| Concrete class | | | C 16/20 | C 25/30 | C 30/37 |
| Reinforcement cross-section | Calculated | cm$^2$ | $A_{s1II}$ = 2.01 | $A_{s1III}$ = 2.01 | $A_{s1IV}$ = 4.81 |
| | Applied | cm$^2$ | $A_{s1p}$ = 10.05 | | |
| Deflection arrow | For condition | cm | $f_{II}$ = 0.07 | $f_{III}$ = 0.25 | $f_{IV}$ = 1.00 |
| | Together | cm | $f_{II} + f_{III} + f_{IV} = 1.32 < f_{max} = 1.65$ | | |

## 5. Time limits when laying the concrete mix

The ceiling in the Stroptronic technology is constructed on supporting walls and/or load-bearing beams, on site, as a fixed, monolithic reinforced concrete slab. In one production run, each portion of the concrete mix, after being combined with water, is immediately transported and by the process of extrusion, embedded in the ceiling band. Stroptronic robot then adds subsequent portions of mixture to the entire vertical cross-section of the ceiling, and full span between the supports, at the same time moving slowly forward at a speed $v$, corresponding to the speed of forming the ceiling, compare Fig. 1.

## 5.1. Minimum speed of forming the ceiling band

Once the concrete bonding process begins, it must be assured of stability. No vibrations of any kind are allowed to affect the laid material. So, all mixing, transportation and embedding has to be finished before the time $t_{pw}$ - beginning of bonding. Hence, the impact of the distribution conveyor of the stacker has to be small and disappear already at a short distance $a$, a dozen or so cm (measured from the cross section $\varphi_o$ on the face of the ceiling 1 to the cross section $\varphi_a$, where the harmful effect of vibrations no longer occurs).

Before the CSA cement starts to set, a large amount of concrete mix should be prepared, so that section $\varphi_a$ moves away from the front of the stacker conveyor $\varphi_o$ by distance $a$. Hence the relationship:

$$t_{pw} \geq t_{mtw} + t_a \tag{5.1}$$

$t_{pw}$ – time interval from the moment of mixing the ingredients with water until the beginning of CSA cement binding, $t_{pw} = 0.53$ h (32 minutes)

$t_{mte}$ – mixing, transport and extrusion time, $t_{mte} = 0.18$ h (for each portion of the mixture: mixing ingredients – 2 minutes, transport and extrusion – 9 minutes, (allowing for its most unfavorable case, where the mixture is transported over a distance of 3 m),

$t_a$ – time of production of the ceiling band, in h, on a section of length a (here: impact of vibrations, $a = 0.12$ m).

Producing the ceiling band at a speed of $v$ m/h in time $t_a$ h, the cross-section $\varphi_a$ will be at distance $a$ m from the stacker, as per the relationship:

$$a = v \cdot t_a\,. \tag{5.2}$$

After transforming the relationship (5.1) and substituting for $t_a$, the minimum speed $v_{\min}$ of laying the band of ceiling (corresponding to the speed of the stacker) should meet the inequality:

$$v_{\min} \geq a/(t_{pw} - t_{mte}). \tag{5.3}$$

Solving for the values above $t_a$, a minimum speed of producing the ceiling band may be very small: $v_{\min} \geq 0.52$ m/h (0,87 cm/min).

### 5.2. Maximum speed of the stacker

In the *Stroptronic* technology, the ceiling is built on site, as a fixed, monolithic, reinforced concrete slab. Underneath the forming ceiling band, move the conveyor and rollers that support the newly made ceiling 1, compare Fig. 1.

In production, several cross-sections were examined and their number defined as $i$, $i = 1, 2, \ldots, k, \ldots, n$. The first cross-section $\varphi_1$ over the edge 16 of the conveyor 15, the second cross-section $\varphi_2$ above the first support roller 17, the third cross-section $\varphi_k$ above the next support roller 18 and the last cross-section $\varphi_n$ above the final roller 19.

Lengths of sections $l_i$, of the ceiling band, measured from the cross section $\varphi_o$, i.e. from the head of forming band to the next cross-section $\varphi_i$, are progressively increasing. Thus, with the speed of the stacker $v > 0$, in subsequent cross sections $\varphi_i$, moving away from the stacker, the ages of concrete $t_i$ are also increasing. Transforming the relationship (5.3), the ages of concrete $t_i$ in a cross section can be determined from this equation:

$$t_i = l_i/v + t_{me},\ i = 1, \ldots, n, \tag{5.4}$$

- $l_i$ – the ceiling length measured from the cross-section $\varphi_o$ (at the head of the band 2) to the cross-section analysed $\varphi_i$, m,
- $v$ – ceiling laying speed (corresponding to the speed of the stacker), m/h,
- $t_{me}$ – mixing and extrusion time, $t_{me} = 0.05$ h (for each portion of the concrete mix: mixing ingredients, as above 2 minutes, extrusion – 1 minute, in the most advantageous case, when laying materials closest to the mixer).

Knowing the age of concrete $t_i$, according to the relationship (5.4) and having determined the characteristic compressive strength $f_{ck(ti)}$ according to the relationship (3.3) i (3.4) and checking the load capacity of the slab according to section 5.1 and 5.2, one can confirm the stability of the ceiling band at each section $s_{i+1}$, $i = 1, \ldots, n-1$.

The maximum speed of the stacker must meet the conditions for each cross-section $\varphi_i$ of the ceiling band being made. Therefore, it should be equal to the smallest speed among all permissible highest speeds occurring in the analysed cross-sections. Thus, transforming the relationship (5.4), the maximum speed of the stacker, in m/h, can be determined from the relation:

$$v_{\max} = \min(s_i/(t_i - t_{me})),\ i = 1, \ldots, n. \tag{5.5}$$

# 6. Verification of necessary ages of concrete in individual cross sections

The ages of concrete in individual cross section depend on the speed of laying the ceiling strand. Thus, below were checked the values of most unfavorable the ages of concrete, which occur at the highest speed of movement the automatic stacker.

## 6.1. The age of beton in cross-section over the edge of the slide plate

In accordance with point 5.1A, the condition for moving the conveyor from under a freshly made ceiling band is to assure, in cross-section φ$_1$ (on the edge conveyor 15), the necessary characteristic strength of concrete $f_{ck(0,7\mathrm{h})}$ = 1.15 MPa, which is achieved at concrete age $t_{0,7}$ = 0,7 h.
For conveyor 15, of width $l_1$ = 0.45 m and of maximum laying speed of ceiling band $v_{\max}$ = 0.68 m/h (1.14 cm/minute), according to the relationship (5.5), age of concrete $t_1$ = ((0.45/0.68)+0.05) = 0.71 h.
Thus, the dimension of the width of the sliding plate $l_1$ = 0.45 m ensures that in the $\varphi_1$ section the concrete age:

$$t_1 = 0{,}71 \text{ h} > t_{0,7} = 0{,}7 \text{ h}.$$

## 6.2. The age of concrete in a cross section above the support roller

According to section 5.1B, in order to ensure the necessary characteristic compressive strength of concrete $f_{ck(1\mathrm{h})}$ = 6.89 MPa, in cross section $\varphi_2$ (above the supporting roller 17) the concrete age should be at least equal to $t_{1\mathrm{h}}$ = 1 h.
For a distance $l_2$ = 0.65 m of the cross section φ$_2$, at maximum laying speed $v_{\max}$ = 0.68 m / h, according to the relationship (5.5), age of concrete $t_2$ = ((0,65/0,68)+0,05) = 1,01 h.
Thus, the distance $l_2$ = 0.65 m from of face the ceiling to the support roller 17 ensures that in $\varphi_2$ cross section the concrete age:

$$t_2 = 1{,}01 \text{ h} > t_{1,0} = 1 \text{ h}.$$

# 7. The ceiling sample made by the Stroptronic machine

The laboratory of the Department of Geo-mechanics, Construction and Geotechnics AGH in Krakow, tested a ceiling sample made by the Stroptronic machine.

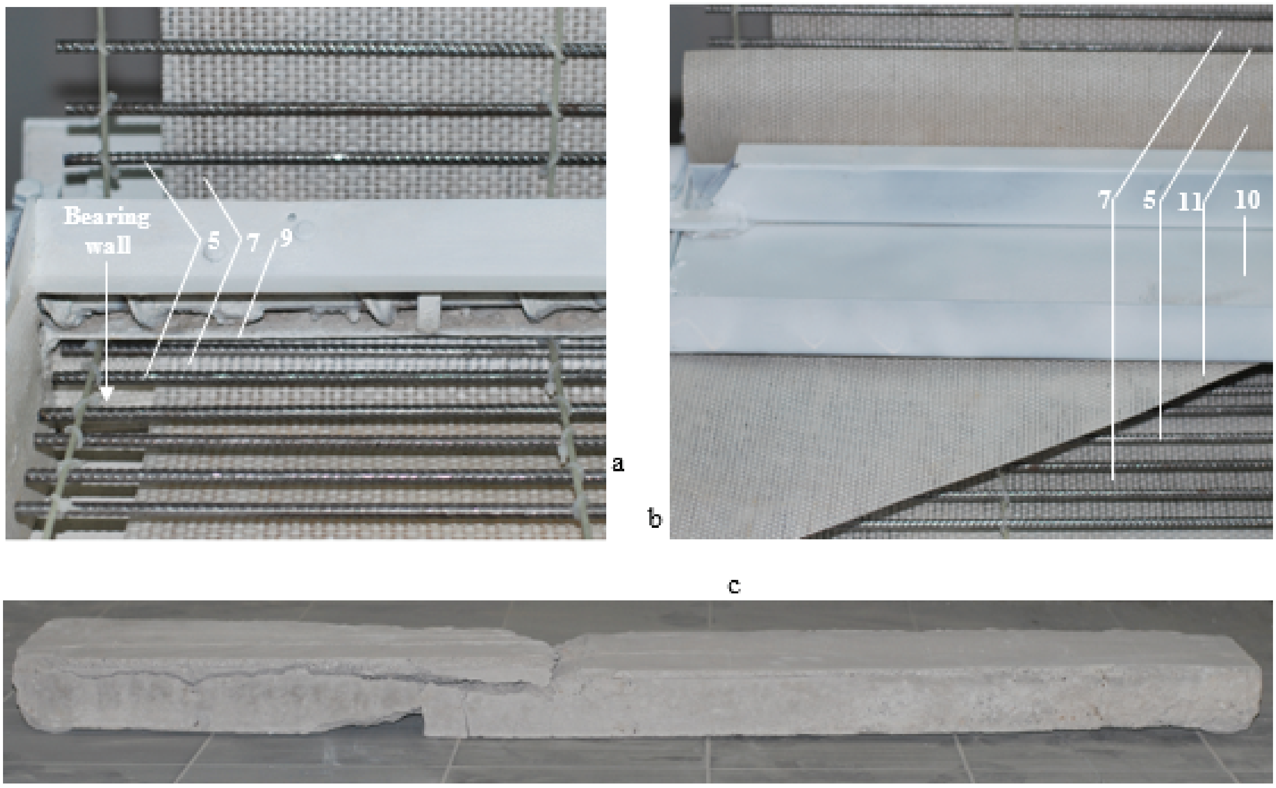


Fig. 5. Method of conducting; a) lower, reinforcement mesh and vapor barrier under the stacker jacket, b) upper vapor barrier under the slab forming the floor surface and c) ceiling sample made with the Stroptronic machine after the destructive test

After 90 minutes of concrete bonding (counted from the addition of water to the last embedded portion of mix), the strength test was performed on the ceiling, based on the following specifications:

- ceiling sample dimensions; length 165 cm, width 20 cm, thickness 8 cm,
- reinforcement mesh; main bars Ø 6 mm, 2.5 cm spacing, A-IIIN steel (RB500), yield strength $f_{yd}$ = 435 MPa; distribution rods Ø 3 mm, 25 cm apart,
- ready-made mixture; Rapid Set® Mixture Korodur on CSA cement [7],
- ambient temperature of materials 20°C,
- the sample made time was 23 minutes.

The test was carried out under the following conditions: support spacing 1.5 m; loading force uniformly distributed linearly over the entire width of the element and applied in the middle of the span of the tested fragment of the ceiling. As above, after 1.5 hours curing of young Rapid Set® Mixture Korodur concrete on CSA cement, the breaking force needed was 14.3 kN.

This test and other systematically performed experiments and checks, including the creep deformations test [18, 21] confirm the feasibility of constructing monolithic ceilings reinforced according to Stroptronic technology and justify the need for further research.

## 8. Summary and conclusions

According to the analysis performed, the following general conclusion can be drawn and based on the test results of standard samples, there are no obstacles:

- to define the function of the compressive strengths depending on the age $t$ – of young concrete with the CSA cement, in the range of 0.7 h $\le t <$168 h,
- to calculate the slab load capacity in significant cross-sections of the ceiling band,
- to determine the speed boundaries: minimum and maximum,
- to use those boundaries for the computer control of Stroptronic stacker during its one pass execution: of a monolithic reinforced ceiling (without support of traditional formwork).

The prototype, proprietary technology *Stroptronic* was presented here to demonstrate the automatic implementation of such a ceiling:

- using an automatic stacker, which in one pass forms and supports the newly formed ceiling band until the supported structure reaches self-bearing state in the cross-section between the target supports,
- ensuring the arrangement of reinforcing mesh and external vapour barriers, dosing of ingredients, their mixing and transport, followed by extrusion of concrete mix and shaping of the ceiling band,
- showing the behaviour of concrete with CSA cement (based on calcium sulfoaluminate) after mixing with water and shortness of time for it to start bonding: 32 minutes, and instant hardening of the concrete and a rapid increase in its early strength: average compressive strength 25.9 MPa shown after 1.5 hours (from the moment of mixing the components with water), using the main reinforcement made of ribbed steel, and the distribution rods made of fibreglass (with shape memory), which allow the mesh to be unrolled just before ceiling production.

Running the Stroptronic device according to the governing algorithm plus constant monitoring, assures the time and quality control, relative to each portion of concrete mix and guarantees that:

- at the minimum stacker speed (in example: $v_{\min} \geq 0.52$ m/h; 0,87 cm/min) the device ensures that each built-in portion of the mix will be moved away from the vibration zone before the bonding start of CSA cement,
- at the maximum speed (in example: $v_{\max} = 0{,}68$ m/h; 1,14 cm/min), the ages of concrete, thus also the compressive strengths in individual cross-sections of the ceiling band, ensure state I – the self-bearing in the cross section between the edge of the slide plate and the first support roller, then between subsequent support rollers. In the cross-section above the last support roller i.e. after 1.5 hours from mixing, the ceiling already reaches the state II of self-bearing capacity.
- after 24 hours, the band reaches the state III of self-bearing, enabling addition of planned layers onto the ceiling. The state IV of full load capacity calculated to suit the target load of the ceiling is reached after 168 hours (a week).

Tests conducted in the lab of Department of Geo-mechanics, Construction and Geotechnics of AGH in Krakow, on the ceiling sample (length of 165 cm, width of 20 cm, thickness of 8 cm, made by an automatic *Stroptronic* device), which absorbed the destructive force of 14.3 kN, have confirmed the correctness of the method and feasibility of its application.

The main advantages of the *Stroptronic* technology include:

- freeing humans from hard labour, and avoiding the need to prepare laborious forms in difficult on-site conditions,
- numerical control of devices, ensuring accuracy and timeliness of works, enables usage of CSA cement,
- small-scale technology, ie low weight and low capital intensity of the solution.

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