Projektnr. TRV / BBT nr:2017-002

Final report

Robotized formless concreting – (RoboBet) – pilot project

Final report

Projektnamn: RoboBet- Robotiserad formlös betong		
Projektnr. TRV / BBT nr:	Projektledare:	Huvudsaklig utförarorganisation:
2017-002	Andrzej Cwirzen	LTU

Abstract

The "RoboBet" was a high-risk feasibility project aiming to validate a novel approach to 3D printing of concrete. The concept is based on a greater control of hardening processes via combination of custom-made capsules containing accelerating substances and additional treatments enabling release of these substances on demand during the printing process.

Several types of accelerating compounds were tested and eventually encapsulated. The produced capsules were mixed with fresh cement pastes and subsequently fractured through the application of ultrasound waves. The released material accelerated the hydration process and shortened the initial setting in some cases.

The obtained results generally confirmed the validity of the concept but the used encapsulation processes significantly lowered the efficiency of accelerators. More basic research focusing on the optimisation of the encapsulation processes must be performed before the actual system can be further developed and eventually upscaled.

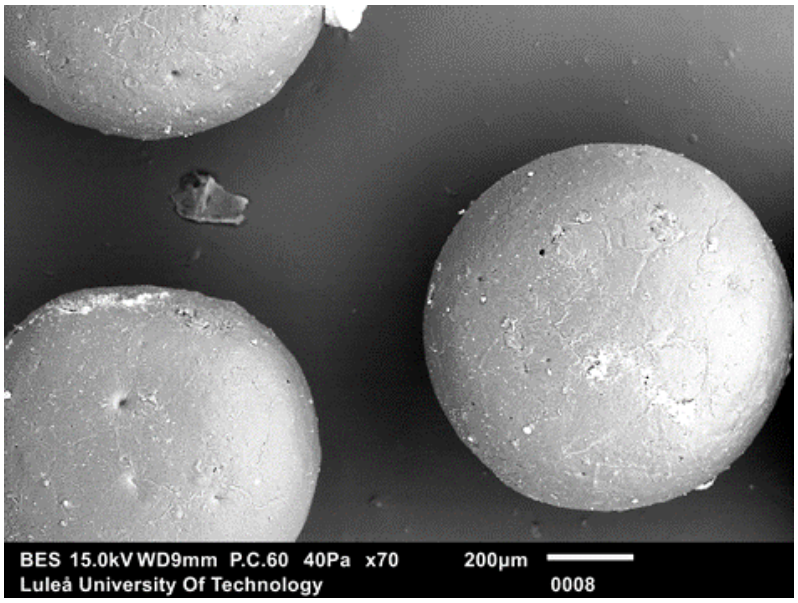

Figure 1 Capsule containing accelerating substance developed during the project

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Abstrakt

"RoboBet" var ett högriskprojekt för genomförbarhet i syfte att validera en ny metod för 3D-tryckning av betong. Konceptet är baserat på en större kontroll av härdningsprocesser via kombination av skräddarsydda kapslar som innehåller accelererande ämnen och ytterligare behandlingar som möjliggör frisättning av dessa ämnen på begäran under tryckningen.

Projektet testades flera typer av accelererande föreningar. De producerade kapslarna blandades med färska cement pasta och sprickandes därefter genom applicering av ultraljud. Det frisatta materialet påskyndade hydreringsprocessen och förkortade den initiala inställningen i vissa fall.

De erhållna resultaten bekräftade generellt konceptets giltighet men de använda inkapslingsprocesserna sänkte acceleratorernas effektivitet avsevärt. Mer grundläggande forskning med fokus på optimering av inkapslingsprocesserna måste utföras innan det faktiska systemet kan vidareutvecklas och så småningom uppskalas.

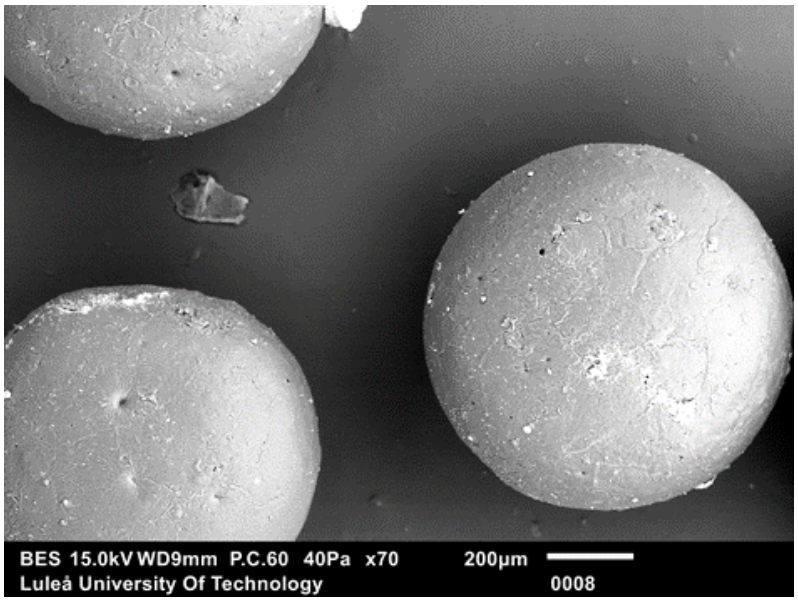

Figure 2 Kapsel innehållande accelererande ämne utvecklats under projektet

Contents

1 Initial project objectives, goals and research questions

The 3D printing technology is very efficient when applied with materials which can be softened by heating and solidified again by cooling, e.g. polymers and metals. In many cases, softening/hardening cycles can be repeated without causing significant changes to the material chemistry, microstructure, ultimate mechanical properties or integrity.

In the case of materials based on Portland cement, the main "obstacle" facing and limiting all currently available 3D printing technologies is an inability to sufficiently control initiation and progress of the cement hydration. As a result the produced solidified material has layered and weak structure. The pilot project aimed to verify a novel concept theoretically developed by the applicant to provide a greater control of setting and hardening of Portland cement based concretes. The ultimate goal is to enable a robotized production of vertical or even partly inclined concrete elements/structures having smooth surfaces, being monolithic and without the need to use any type formwork, Figure 2.

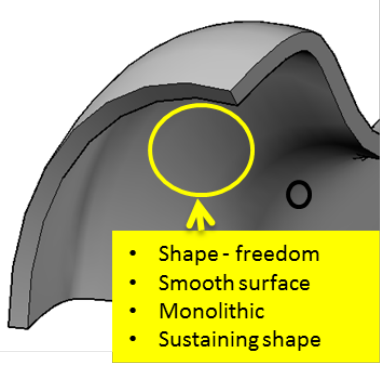

Figure 3 The ultimate goal.

In order unfold a full potential of 3D printing of concrete; hardening of Portland cement must be controlled to a greater extent. The following "research questions" were formulated:

1) *Is it possible to initiate "on demand" rapid setting of Portland cement?*
   - *Answer: Yes but with certain limitations*
2) *Is it possible to control (limit) the volume of concrete where setting "on demand "will be initiated?*
   - *Answer: Yes but with certain limitations*
3) *Is it possible to limit the accelerated hydration of Portland cement to only selected volumes?*
   - *Answer: Yes but with certain limitations*
4) *What are potentially the best combinations of processes/ materials enabling control of setting and hydration, which are suitable for application in robotized 3D printing system?*
   - *Answer: Normal Portland cement + capsules with accelerators + ultrasound waves*

2 Execution of the project shown according to the work packages

2.1 WP1 – STAR

The 3D concrete printing market size is estimated to grow from USD 24.5 Million in 2015 to USD 56.4 Million by 2021. The productivity is expected to be increased and the design-execution process to be shortened. It is estimated that 3D printing of concrete **will reduce construction waste by 30-60%, production time by 50-70% and labour costs by 50-80%[1].** Existing technologies for 3D printing of concrete produce very low surface quality, and layered "sausage-like" structure, Figure 2. Overview of few existing 3D printing methods vs. traditional and cast in-situ is shown in Table 1. The first example is "smart dynamic casting" (SDC), which is a combination of slip forming with digital fabrication techniques[2345]. It enables digital transfer of designed models into full structures by using a slip forming technique. SDC technology can produce monolithic elements with good surface quality but is restricted to vertical columns only. Another example is "concrete printing", based on joining materials to produce full-scale objects or structures layer after layer from 3D model data[678910]. The system is based on a printing head digitally controlled by a CNC machine enabling movement in X, Y and Z directions. The machine uses self-compacting concrete. "Contour crafting" takes the "concrete printing" technique further to create an integrated production system enabling design, reinforcement and installation[1112]. The produced elements have low surface quality, layered structure, and can be only vertical.

The 3D printing process requires the material to be easily formed to travel through the feed/nozzle system onto the formed element, but then it should harden on demand and develop sufficient strength. In addition, it should bonding well with previously formed layers. It is not a problem in the case of polymers or metals, which soften when, heated and solidify when cooled down but in the case of concrete where all binding is provided by hydrating Portland cement application heating/cooling cycles is not possible. Once Portland cement is mixed with water, it starts to reacts and, depending on temperature, sets at certain point of time and starts to develop its strength. There is very little control over these processes when looking at times intervals counted in seconds and minutes, as required during 3D printing. If cements will set too slowly the form-less elements will not keep their shape. If cement will set too fast, each subsequent layer will not bond sufficiently with previously "printed" layer. Most currently produced structures using 3D printing of concrete have exactly these problems, Figure 2.

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[1] https://www.smitherspira.com/products/market-reports/printing/the-future-of-3d-printing-to-2025
[2] Lloret et al (2015) Comput-Aided Des 60:40–49
[3] Cesaretti et al (2014). Acta Astronaut 93:430–450
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[5] Pegna (1997) Autom Constr 5:427–437
[6] Buswell et al (2007) Autom Constr 16:224–231
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[8] Le et al. (2012) Mater Struct 45:1221–1232
[9] Le et al. (2012) Cem Concr Res 42:558–566
[10] Lim et al. (2012) Autom Constr 21:262–268
[11] Zhang et al. (2013) Autom Constr 29:50–67
[12] Koshnevis et al (2006) Int J Ind Syst Eng 1:301–320

Table 1 Summary of existing 3D technologies (red: disadvantage, yellow: neutral, green: advantage)

Casting techniques	Formwork	Surface quality	Shape stability	Monolith	Horizontal elements	Digitali-zation	Design freedom
Cast-in-situ	Yes	Very high	Extreme	Yes	Yes(1)	No(2)	limited
Precast concrete	Yes	Very high	Extreme	Yes	Yes(1)	No(2)	limited
SDC (3D)	Yes (3)	High	Good	Yes	No	Yes	limited
Concrete printing(4)	No	Low	Acceptable	Layered	No	Yes	Improve
Contour crafting (3D)	No	Low	Acceptable	Layered	No	Yes	Improve

(1) Elements produced in formwork, (2) No direct transfer, (3) Modified, (4) Using regular concrete technology, (5) Highly inclined elements and possibly horizontal

2.2 WP2 - Materials

Initially this WP was planned to focus on development of a number of mortars and concrete mixes. However, due to the inability of SINTEF to provide the capsules with various accelerating admixtures the focus on that WP was changed to the synthesis. A chemical engineer was assigned to develop the method.

The work package focused on encapsulating of several types of accelerators and testing its stability and fracturing while applying ultrasound.

In the first step, effects of various types of accelerators were evaluated to verify a possibility of inducing the flash set required for the printing process, Table 2.

In the second step, the most promising substances were evaluated in terms of their effects on setting times, Table 3. As a result, the following substances; were chosen for the main part of the study, which focused on their encapsulation sodium silicate solution, industrial sodium carbonate and calcium nitrate. Encapsulation was done using three types of methods, which will be described briefly in the following section.

Table 2. Evaluation of the potential for the flash set of various accelerating substances. F= Failed S=Succeed Na2CO3, P = Pure A.Kaolin= Activated

Test	Cement(g)	H20(g)	$NaHCO_3$(g)	Na_2CO_3(g)	Na_2CO_3, P(g)	Ca(NO3)2	A. Kaolin(g)	Na_2SiO_3(g)	F/S
1	9	4.6	1						F
2	9	4.5		1					F
3	8	4.5		2					S
4	8	3.5		2		2			S
5	8	3.6							F
6	9	3.5		1					S
7	9	3.5			1				S
8	9	4.5			1				S
9	8	3.5			2		2		S
10	8	3.5							S
11	8.5	3.5			1.5				S
12	9	3.5						1	F
13	8	3.5						2	F
14	10	1.5						2	F
15	10	3.5						2	S

Table 3. Setting time assessed with Vicat apparatus

	Mix1	Mix2	Mix3	Mix4	Mix5	Mix 6	Mix 7
w/c	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Na2SiO3		10%			5%		
Na2CO3			5%				
K2SO4				5%			
Na2CO3						5%	
Ca(NO3)2							5%
Initial setting time	170 min	30 sec	2min	2min	10 min	5min	~30min

2.2.1 Encapsulation

Encapsulation was done using two techniques: polymerization and pan coating. The following section will described in more details the obtained results.

2.2.1.1 Polymerization

Polymerisation was done using real formaldehyde, double shell polyurethane and polyvinyl alcohol depending the substance being encapsulated, Figure 3. After chemical processing capsules were separated by filtering and dried, Figure 4.

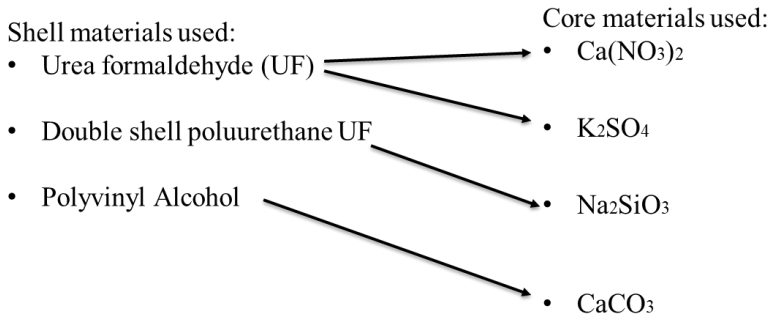

Figure 4. Used shell core materials vs encapsulated accelerating substance

Figure 5. Experimental setup used for filtration of the synthesized capsules and filtered product

- Ca $(NO_3)_2$, Calcium nitrate core coated with poly urea formaldehyde (UF) shell.

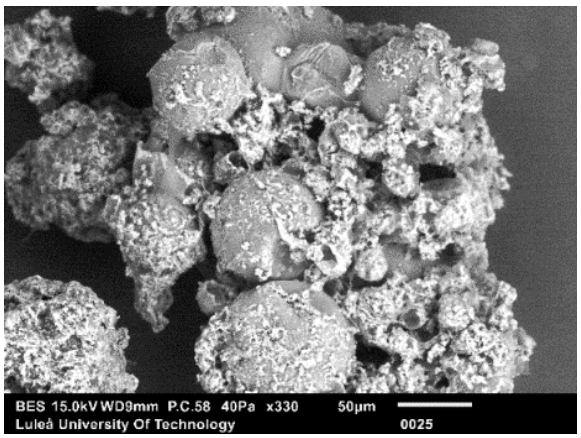

Figure 6. Urea formaldehyde capsules containing calcium nitrate

- K_2SO_4, Potassium sulfate as core material coated with Poly urea formaldehyde (UF) shell.

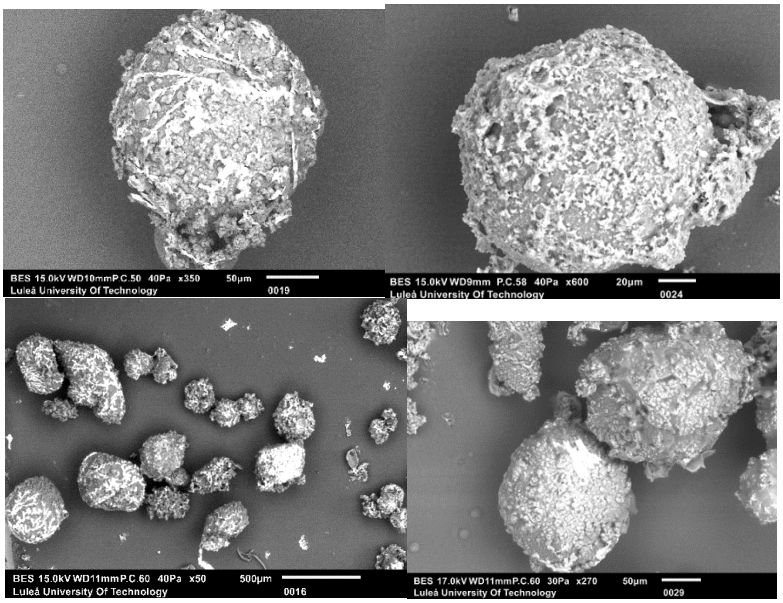

Figure 7. Urea formaldehyde capsules containing potassium sulphate

- Na_2SiO_3, Sodium silicate (water solution), as core material coated with double shell of polyurethane-urea formaldehyde (PU-UF)

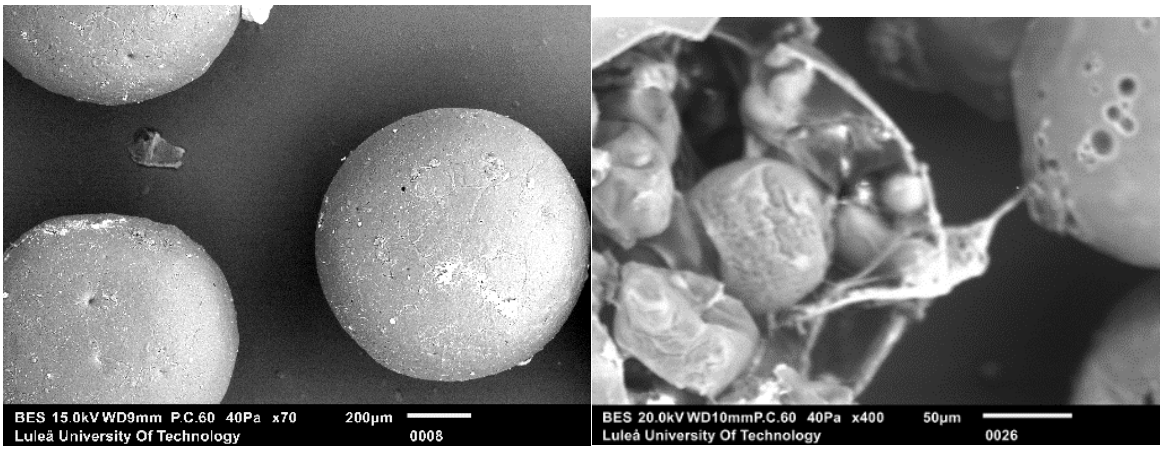

Figure 8. Double shell poluurethane capsules containing sodium silicate

2.2.1.2 Pan coating

In this approach, a polyvinyl alcohol dissolved in solvent was sprayed in a pan that contained $CaCO_3$. Calcium carbonate was coated with a thin film of polyvinyl alcohol. (Capsule had very strong shell and core release was impossible

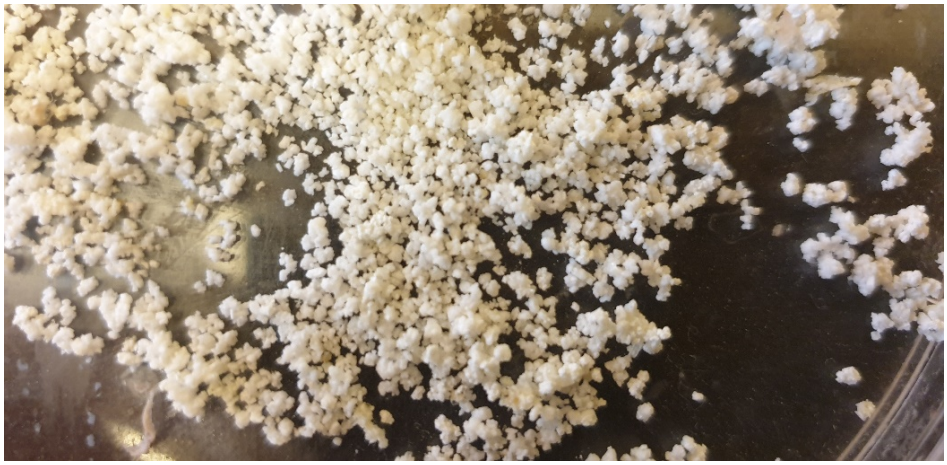

Figure 9. Capsules produced using the pan coating procedure and containing calcium carbonate

2.3 WP3 process

The main objective of this work package was to evaluate the effectiveness of capsules to accelerate setting and hardening of developed mixes on demand. The basic measured parameters included setting times and flash setting as well as effects of ultrasound and microwaves.

2.3.1 Treatments

Ultrasound effect and microwave effects were studied. In the first step, the encapsulated material was mixed with a distillate water. The capsules did not react with water. In the second step, ultrasound was applied. The results showed cracking of capsules and release of the accelerating admixtures, Figure 9.

Figure 10. Capsules in water before and after ultra-sonication.

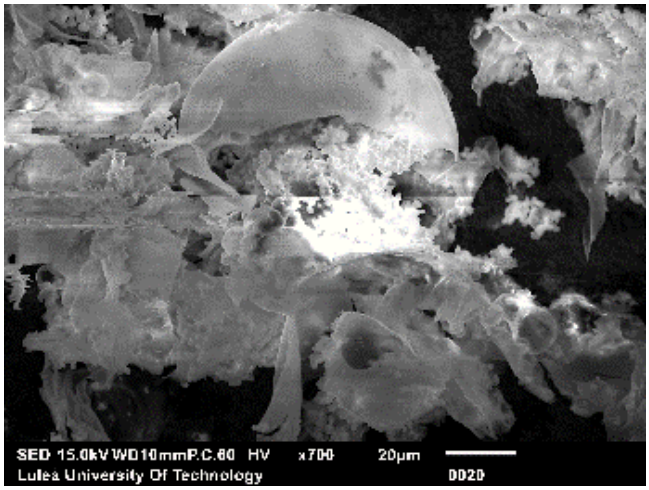

Figure 11. SEM image of fractured microcapsules after application of ultra-sonication.

Capsules were mixed with cement paste to evaluate their effect on setting time after treatment with either ultrasound of microwaves. Example mix designs and obtained initial setting times are shown in Table 4. All cement paste mixes had the W/B ratio of 0.4, and contained either 0 or 5 wt% of capsules. The results showed that the reference mix had the initial setting after 184 minutes. Addition of capsules containing potassium sulphate and potassium carbonate elongated that time to up to 310 minutes independently of the used treatment.

Good results were obtained when using capsules containing calcium nitrate. In that case, the setting time was shortened from 185 minutes to 95 and 82 minutes. However, in comparison with pastes containing those accelerating substances as added directly to the mix the time were significantly longer. For example, mix incorporating 5w% of calcium nitrate showed setting already after 30 minutes vs 82 minutes when encapsulated. Even more extreme differences were observed for other admixtures where for example sodium carbonate caused setting already after 3 minutes while when encapsulated as retardation to 230 minutes was measured. Those results clearly indicate that the chemical composition of the used accelerating materials was altered during the encapsulation process. Further studies limiting or excluding that trend should be performed.

Table 4. Initial setting time for pure cement paste (Ref), mix of cement paste with capsules subjected to additional treatments; ultrasound (US) or Microwaves (MW).

	Ref.	C1B	C1BM	C2B	CNBa	CNB
Treatment	no	US	Micro wave	US	US -bath	US
w/c	0,4	0,4	0,4	0,4	0,4	0,4
Capsule K2SO4	0%	5%	5%			
Capsule K2CO3	0%			5 %		
Ca(NO3)2	0%				5%	5%
Initial Setting Time (min)	184	310	230	277	95	82

Additional tests on effect of microwaves on fresh cement paste properties were studied using 600 Watts power setting. The results showed that al mixes were dried or showed a significant delay of the setting time, Table 5.

Table 5. Microwave effect of cement paste, 600 W

	Mix 1	Mix 2	Mix 3	Mix 4	C
cement	50	50	50	50	50
water	20	20	20	20	20
w/c	0,4	0,4	0,4	0,4	0,4
MW(sec)	30	20	10	5	No MW
Initial Setting Time (min)	Drying of the mix	Drying of the mix	260	280	225

2.4 WP4 – Analysis and dissemination of the results

All obtained in WP2 and WP3 test results were constantly analyzed during the project, which resulted in development of several processes enabling encapsulation of accelerating admixtures, which were initially planned to be delivered ready by an external supplier. The inability of that delivery resulted in a slight alteration of the project as described in WP2 and WP3 and development own technology. On the negative side, originally planned tests with a combination of retarders + rapid hardening cement and half-scale tests aiming to determine the extent of the affected by US volume of concrete had to be abandon.

One journal paper in Swedish language will be prepared in the year 2020. The reference group meeting will be organized in connection with another TRV-BBT project focusing on self-healing of concrete in late autumn 2020 where results will be discussed and recommendation about future steps will be formulated.

3 Summary and recommendations

3D printing technology is entering modern world at an accelerating pace. Concrete industry also developed some solutions as shown in the STAR section of this report. Most of current limitations are related to the nature of concrete which is usually based on Portland cement, which once mixed with water starts to irreversibly react, set and harden. Current solutions are based on utilisation of concrete mixes compromised to provide at the same time sufficient green strength, adequate strength development and sufficient workability. Consequently, the printed structures do not keep properly shape and must be vertical only.

The described in this final report concept is based on an innovative idea to provide an “on demand” initiation of a rapid hardening/stiffening process. The method is based on incorporation into concrete mix microcapsules containing accelerating materials, which will be fractured by ultrasound generators installed in the printing head. The system will enable to release accelerating admixtures only in the required volumes as for example excluding the very top layer, which will provide the bond.

Several types of accelerating compounds were encapsulated and tested for their efficiently in pastes after being released due to ultra sonication.

The obtained results generally confirmed the validity of the concept but due to involved chemical processes used during encapsulation the effectiveness of accelerating substances has decreased. More optimisation testes focusing on the encapsulation processes must be performed before the actual system can be further developed.

4 Financial report

See appendix A