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GREEN IS GOOD: FIRST RUN STUDY OF A SUSTAINABLE BUILDING STRUCTURE

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ABSTRACT

The study made an account for in this paper is based on the hypothesis that introducing a climate-friendly building material to construction production may fundamentally impact project performance. In the paper, evidence is given for a prolonged, costlier process of erecting the building structure if an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied. Findings suggest various measures to be taken, to accelerate the hardening of the concrete. Otherwise, a positive environmental effect may easily diminish the overall project performance. The paper is based on a First Run Study (FRS) including a full-scale mock-up of a part of the building structure, including ground floor, wall, columns, and slab. As part of the study, data was collected about the temperature, firmness, and relative moisture of the concrete, and the effects of different actions applied to accelerate the hardening process. The impact of this study is an estimated risk reduction of 1,5 percent in the context of the project it was intended to support. The paper concludes that this type of experimentation should happen prior to actual performance to prevent construction projects from falling short of time and finances caused by unexpected results.

KEYWORDS

Lean and Green, First Run Study.

INTRODUCTION

In the first run study presented in this paper, an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied in a physical mock-up on site. The research carried out investigates whether – and under what conditions – it is feasible to use this substance in the building structure of a five-floor high, 11 000 square metres office building. The completed structure will be the first of its kind using this type of concrete to the full. To deliver the project is Veidekke, one of the largest general contractors in Norway. As part of its climate strategy, the company will reduce greenhouse gas emissions by 50 percent by 2030. An overview of emission sources from all building and civil engineering-related activities in the company shows that the use of concrete stands for as much as 31 percent of the total 269 000 tons of CO^2 emissions. Veidekke is also on the client side of the project, in companionship with OBOS, Norway's largest housing developer. Together, they have decided that the new-building project should at least contribute to a 50 percent reduction in greenhouse gas emissions. This makes it a primary concern to initiate changes that really make a difference in sustainable development.

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To prevent global warming beyond 1,5 °C above pre-industrial levels, the Intergovernmental Panel on Climate Change (IPCC) has concluded that greenhouse gas emissions must decline by 43 percent by 2030 and to net zero by 2050 (UN DESA 2022). Then being green, for lack of a better word, is good. Green here alludes to a mindset based on ensuring that activities, be they individual, corporate, or otherwise, reflect an overall concern for safeguarding the planet Earth and its natural resources. The construction industry generates about 38 percent of annual total greenhouse gas emissions globally (United Nations Environment Programme 2022). Size matters in this respect, the construction sector being one of the largest in the world economy, with about $10 trillion spent on construction-related goods and services every year (McKinsey Global Institute 2017). Furthermore, the cement and concrete industry is responsible for about 8 percent of global carbon dioxide emissions, more than double those from flying or shipping (Niranjan 2022). This means that, in the efforts to make a difference, the industry's attention needs to be drawn specifically to the emissions produced elsewhere and brought into construction production in form of building materials. The results presented in this paper can thus be of great value to an industry with a huge potential to turn the heating process on the planet down.

FIRST RUN STUDIES

First Run Studies were introduced by Ballard and Howell (1994) as a method to improve downstream performance, by changing how we do the work. The method is linked to craft operations and described as a process where the operation is examined in detail, where ideas and suggestions are requested from all parties, and experiments are performed to explore alternative ways of doing the work. The study ends with the definition of a performance standard, which in turn is challenged to meet or beat the best done thus far (Ballard and Howell 1994). A First Run Study reminds of the Plan-Do-Check-Act (PDCA) cycle, which was popularized by W Edwards Deming (Aguayo 1991). The cycle, also known as the Deming cycle, describes a simple method to test information before making a major decision. When running an experiment, the first step includes planning (or designing) the experiment, the next performing the experiment, and thereafter, checking the results by all the information gathered through the test, before acting upon the decisions based on those results (Aguayo 1991).

In the manufacturing industry, the concept of pilot production has evolved under somewhat the same line of reasoning as the PDCA cycle. Pilot production is typically applied to verify a new product and its production system. Almgren (2000), using the experiences of the Volvo Car Corporation, describes pilot production and manufacturing start-up as two processes that greatly affect development costs, time to market, and product quality. Pilot production refers to pilot runs carried out in a production system intended for commercial use. During pilot production, pilot vehicles are built and assessed from a product and production system perspective. Pilot production aims to identify and prevent disturbances affecting the final verification before the start of volume production (Almgren 2000). Manufacturing start-up is typically divided into two sequential phases, low-volume and high-volume production, where low-volume production is done to fine-tune the factors affecting performance before high-volume production (Almgren 2000).

In the IGLC conference proceedings, First Run Studies are scarcely represented. An interesting contribution to the topic is done by Tsao et al. (2000), which – even though it does not include a real first run – exemplifies the potential use of the method to prepare the installation of metal door frames at a prison project. In prisons, the door frame installation differs from the usual due to added security measures. The paper underlines that to improve the process of installing frames, different perspectives need to be considered. The authors conclude that this rarely happens, as all parties are seldom brought to the table to consider work structuring together early enough (Tsao et al. 2000). In the authors' view, thinking about system-wide solutions is also hampered by a contracting mentality. Instead of questioning a bad design, a worker complains and works around it, because their contracts are already signed, and work must proceed (Tsao et al. 2000). A few years later, altogether three real First Run Studies are presented to the IGLC by Saffaro et al. (2006), to investigate the role of it as an experimentation technique. The authors conclude from these studies that production constraints typically interrupt a proper application of the cycle observation-reflection-action, thus leading them to question the capacity to deal with prototyping issues in a dynamic environment (Saffaro et al. 2006).

Construction production, it seems, is not very suitable for experimentation. Koskela (2000) has a somewhat alternative perspective, seeing the actual building as a prototype where the production stage is used to eliminate errors generated in the design or production planning processes. Does this mean every construction project is a first-run exercise? To the point it is, Saffaro et al. (2006) suggest that virtual models must be used to eliminate design uncertainties and errors, thereby removing product-related problems that do not allow the prototyping exercise to focus on work methods and standards. At the same time, production in construction is always locally bound and dependent on physical factors such as soil and weather conditions (Vrijhoef and Koskela 2005). While virtual models, most certainly, are helpful to reduce design uncertainties and errors, they cannot replace the transformation of the design into physical reality which must still rely on the use of physical mock-ups (Pietroforte et al. 2012).

METHOD

The First Run Study was carried out, using a combination of laboratory testing and a physical mock-up. In addition, a digital model was developed to visualize all the planned actions to be taken on different parts of the physical mock-up. The laboratory testing was carried out to test different combinations of concrete, specifically focusing on the effects of using a recycled versus a normal aggregate. The physical mock-up was erected in situ, at the exact same site as the later office building is being built. The mock-up was done in the winter to test how the extremely low-carbon concrete responded to low-temperature exposure.

1. The digital model was used:
    a. To make a visual representation of the physical mock-up
    b. To identify which actions should apply to various parts of the physical mock-up
    c. To do quantity calculations and take-offs from the model, as part of planning the structural work
2. Laboratory testing was necessary:
    a. To test the elasticity, firmness, and relative moisture of the concrete combined with the use of the recycled aggregate
3. Use of the physical mock-up allowed:
    a. To collect reliable data about the concrete and structure
    b. To include air temperature in the evaluation
    c. To measure the effect of different actions, on the hardening process

For the testing performed in the laboratory, different tools were applied. To test the elasticity of the concrete, fresh concrete was poured into small, cubic-formed containers which in turn were exposed to vibration. To test the concrete’s firmness, the cubes were later exposed to pressure using a manometer to measure the megapascal. To measure the relative moisture in the concrete, a moisture meter was applied.

A physical mock-up was erected, about 100 m² in size, and including 27 m³ of concrete. The building structure was cast in place, using post-tensioned reinforced slabs. Every cast was monitored, using concrete sensors to measure the temperature, strength, and maturity of the concrete. Several actions were applied to accelerate the hardening process, amongst others including heating pipes containing glycol, hot air fans, infrared ovens, insulation plates, surface accelerators, polyethylene foam, and heating cables.

RESULTS

THE RECYCLED AGGREGATE

The laboratory tests were done partly to find out more about the quality of the recycled aggregate, partly to investigate the effects of using it in fresh concrete, and partly to study how the concrete appears when using 100 percent recycled aggregate.

The quality of the recycled aggregate was controlled using several measures, amongst others to check the density and variation in the size of grains, their ability to absorb water, and their chemical composition. This is because the quality in turn will determine how the concrete appears. The control checks uncovered that the recycled aggregate had much the same quality as virgin aggregates.

To test the workability of the fresh concrete, a slump was poured into a funnel-shaped form which was pulled up to measure how much the substance floated (Figure 1). Thereafter, E-module testing was done on concrete cylinders (Figure 2), including the use of equipment to measure (and regulate) the elasticity of the concrete.

Figure 1: Controlling the workability of the fresh concrete

Figure 2: E-module testing

THE PHYSICAL MOCK-UP

The physical mock-up was erected in Oslo, Norway, in February-March 2021. The middle temperature in the area is then -2 °C. The timing was decided because the weather was an important parameter to include in the tests. To control for variations, the outdoor temperature was logged on a regular basis. The structural work, including the ground floor, supporting walls, columns, and slab, was a replica of a part of the office building later to be built. After all the tests were completed, the mock-up was demolished.

The ground floor

The ground floor was divided into four fields, to which different actions were applied to be able to control their effects (Figure 3). Field 1 included the use of a surface accelerator and covering up by using polyethylene foam directly after the cast. The cast was done directly on the gravel. Field 2 included the use of insulation underneath the cast, membrane curing, and covering up when the cast was ready to walk on. Field 3 included the use of heating pipes, membrane curing, and covering up when the cast was ready to walk on. The cast was done directly on the gravel. Field 4 included the use of insulation underneath the cast, heating pipes, membrane curing, and covering up when the cast was ready to walk on.

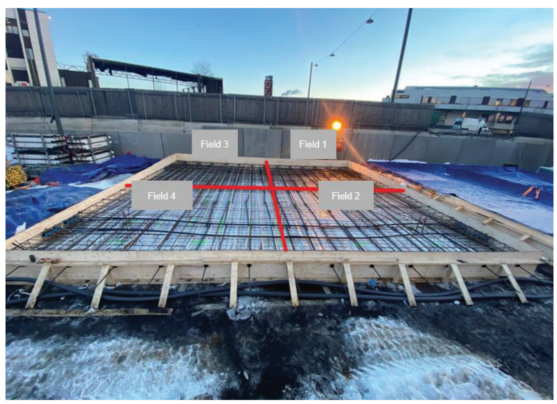

Figure 3: The ground floor, including the four fields

Findings related to the ground floor (Figure 4) show that the temperature in the fresh concrete drops heavily, especially in field 1 which include only limited actions and where the cast is done directly on the gravel. This has to do with the extremely low-carbon concrete, which develops no heat of its own. Thus, if the cast goes on in the winter, actions will be necessary to avoid a drastic temperature drop. Of all the actions applied, the most effective combination seems to be the one used in field 4 with insulation underneath the cast, heating pipes, membrane curing, and covering up when the cast is ready to walk on. The temperature development in the concrete affects the hardening process. As a result of the extremely low-carbon concrete being a "dead" substance, the hardening process is delayed and occurs only after 20 hours or more. When measured in megapascals, it takes about 24 hours for the ground floor in fields 2 and 4 to have reached an acceptable level of strength (5 megapascals). From the findings, one may conclude that especially heating pipes and insulation appear to boost the hardening process.

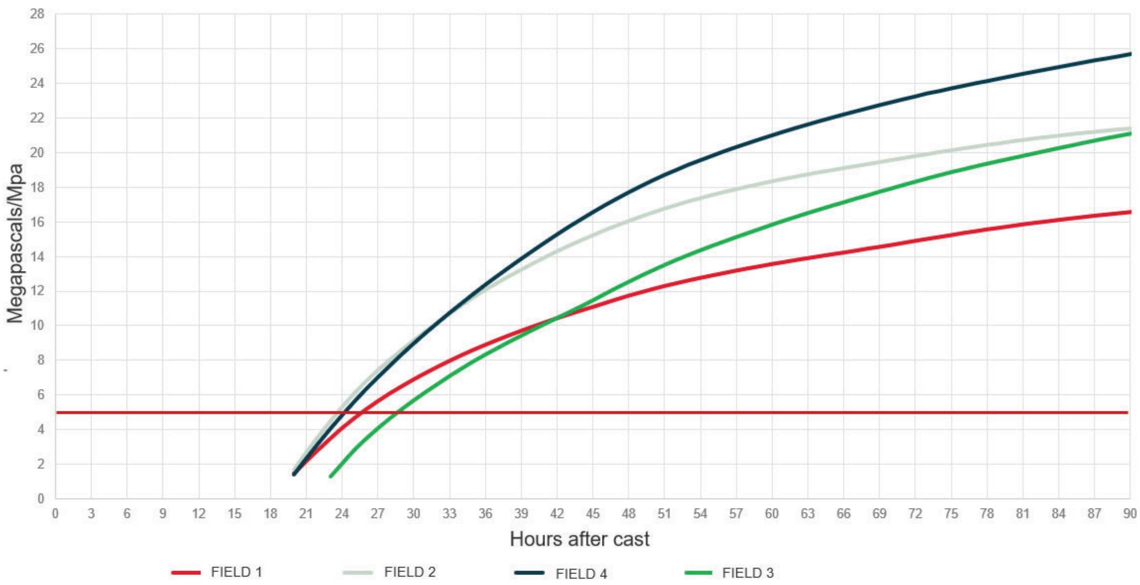

Figure 4: Hardening process of the ground floor

The columns

Altogether four columns were included in the mock-up. Different measures were applied to each of them (Figure 5). Column 1 was insulated by a double layer of polyethylene foam, while column 2 had only one layer of insulation. Column 3 had heating cables included in the concrete, in addition to one layer of insulation. Column 4 had heating cables on the outside, underneath one layer of insulation.

Figure 5: The four columns

Heating cables, either in the concrete or on the outside, seem to have a positive effect on the hardening process. For the two columns including this measure, it takes about half the time to reach the acceptable level of strength (8 megapascals) compared to the columns with only insulation.

The wall

The wall surfaces were split in two, where the upper parts included no measures while the lower parts included subsequently heating pipes containing glycol on one side and heating cables on the other (Figure 6).

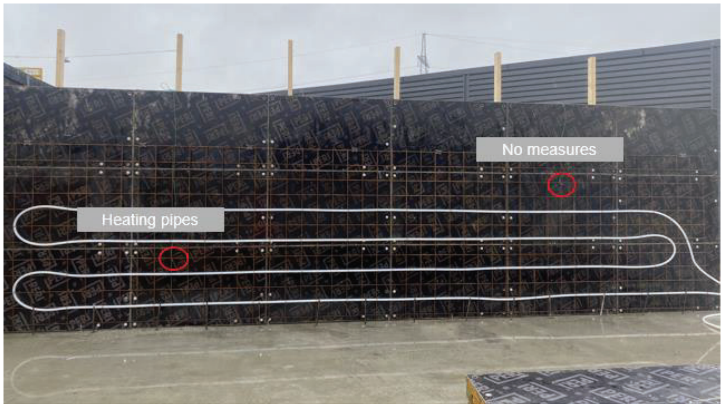

Figure 6: Wall surface, including heating pipes

The temperature development indicates a sudden and steep effect of both heating options. Furthermore, the hardening of the wall using heating cables or heating pipes seems to be all the same, both requiring between 15-18 hours to reach an acceptable level of strength (5 to 8 megapascals). In comparison, around 30 hours or more are required before the same level is reached when no measures are used.

The slab

Four different measures were tested to improve the hardening of the slab, which moreover was divided into several fields. The most comprehensive method applied was where the area underneath the slab was covered by insulation and hot air was pumped into it and circulated (Figure 7). Other actions underneath the slab included the use of infrared ovens and insulation plates, whereas heating pipes were tested in the slab.

Figure 7: Slab, with hot air underneath

Findings indicate that heating pipes in the slab are the most effective solution among those tested to improve the hardening process (Figure 8). Applying this measure, it takes 38 hours for the slab to reach the acceptable level of strength (25 megapascals). It also appears to give good results if insulation plates are used underneath the slab. On the opposite side, if no actions are taken underneath or in the slab, it may take 100 hours or more for the slab to reach the acceptable level of strength.

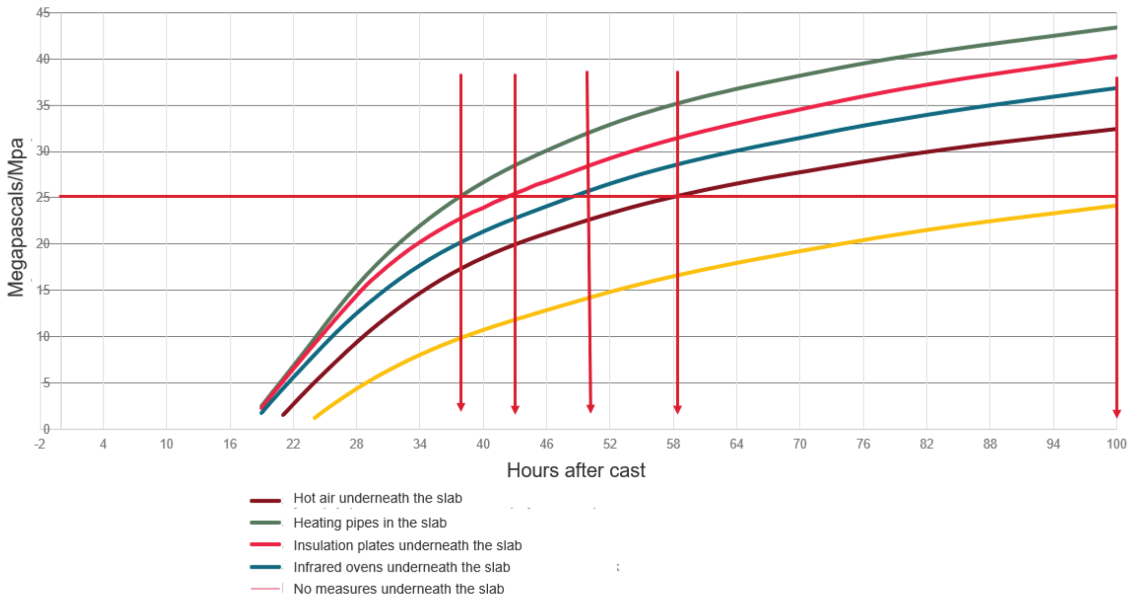

Figure 8: Hardening process of the slab

DISCUSSION

If using extremely low-carbon concrete, what would be the ideal measures to apply to improve the hardening process when erecting the structural envelope? Based on the results presented in this paper, different measures seem to apply to the various elements. Regarding the ground floor, the most effective combination is when insulation is placed underneath the cast, heating pipes in the cast, membrane curing, and covering up when the cast is ready to walk on. On the columns, heating cables on the inside or the outside have a positive effect. As for the wall, somewhat the same can be said about heating pipes and cables, whereas in terms of the slab heating pipes in the concrete seems to give the best results. On the opposite side, if no actions are applied using extremely low-carbon concrete, the findings presented here indicate a late hardening and substantially prolonged structural building phase. This is because the extremely low-carbon concrete develops no heat of its own. When having to deal with this substance, the simple answer to the question above is thereby to make use of all these actions.

Following this First Run Study is the office building constituting 11 000 square metres and consisting of 3900 m^3 of concrete. While there is no calculation of the total costs of applying all the measures described, it will inflict additional expenses on the project. This would necessarily mean that the client needs to find it appropriate to spend the extra money. From a client's perspective, the cost of doing it will naturally be weighed against alternatives. For instance, how much will the project be delayed if no measures are used, weighed against the potential time savings of applying them? All the actions considered; this question seems particularly relevant to address to those meant for the hardening of the slab. If no or only simple measures are applied here, it takes a minimum of 100 hours before the slab has reached an acceptable level of strength (25 megapascals). A hardening process thus long would substantially delay the production progress.

This moreover triggers another consideration related to which actions should be prioritized if the focus was on choosing one or a few that would be the most effective. The actions meant for the slab seem particularly relevant in this respect. At the same time, all the rigging and equipment needed to apply at least some of these actions brings the cost concern into the equation. Then, the use of insulation plates underneath the slab might be the optimal choice. Even though heating pipes in the slab are slightly more effective in terms of hardening, it is also more expensive. Not necessarily due to material costs alone, but because of the power supply needed to be combined with the use of the pipes. At the same time, if the outdoor temperature falls drastically – which might very well happen in Oslo in February – then using heating pipes is likely the best alternative, even though applying it may cost more.

What if the process of erecting the structural envelope goes on in the summer instead of winter? Considering that extremely low-carbon concrete develops no heat of its own, it would seem a plausible strategy to do the cast in a period of the year when a much warmer atmosphere could help the hardening process go faster. What is more, it would save the project from additional expenses due to the various actions discussed above. Even more so, it would save the environment from emissions at the construction site, in form of material waste and energy consumption caused by the actions described. Since the mock-up was erected in the winter, there is no data to describe the effects of doing the cast at another time of the year. That said, the main problem seems to be the lack of heat inside the concrete, which delays the hardening process. Furthermore, when the substance is exposed to heat from external factors, it exhibits a positive response in terms of a more rapid hardening. After all, what can be more environmentally friendly than using the sun's warmth to make this happen? Ultimately, the solution must be to do the cast in the summer period if extremely low-carbon concrete is used.

Given the ultimate solution listed above, was the physical mock-up and all the testing a waste of time and money? No, because insight beats hindsight. Due to the use of a new substance, risks in the project's uncertainty analysis carried out were considered particularly high for the structural building phase. As a result of the first run study, the project's uncertainty was reduced from 4 to 2,5 percent of the total contract sum on 410 MNOK. A pilot production costing approximately 1,5 MNOK thereby paid off several times as uncertainty dropped from 16 to 10 MNOK.

CONCLUSION

This paper gives support to the hypothesis that introducing a climate-friendly building material to construction production may fundamentally impact project performance. Evidence is given for a prolonged, costlier process of erecting the building structure if an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied. A First Run Study (FRS) involving a physical mock-up proved very useful to uncover which actions are the most effective to accelerate the hardening process. The impact of this study was an estimated risk reduction of 1,5 percent in the context of the project it was intended to support. This type of experimentation should happen prior to actual performance, though, to prevent construction projects from falling short of time and finances caused by unexpected results. The outcome of this study is knowledge about how extremely low-carbon concrete appears in cold conditions. Without it, it would be less obvious that cast in the summer has clear-cut advantages. In fact, one can even imagine that cast in the winter could be initiated without further hesitations, with potentially devastating results. Additionally, while it is clear and obvious that doing the cast in the summer is the best alternative, this is not always a choice. A construction project evolves at the mercy of many conditions, whereof some are more difficult to control than others. To reach a timing in every project that fits perfectly with a schedule saying that the cast should only go on in the summer is a very naïve approach to handling the problem. Rather, it would seem a more passable way to go, to learn from the First Run Study presented in this paper which actions seem most appropriate to apply in your project and avoid experimenting too much once the production gets going.

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