INDUSTRIAL CASTING OF BRIDGES COMBINING NEW PRODUCTION METHODS AND MATERIALS, LIKE A ROBUST SCC, UTILIZING LEAN CONSTRUCTION PRINCIPLE

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Abstract
The implementation of SCC in addition to new reinforcement and form techniques make it possible to increase the degree of industrialisation at construction sites markedly. It has been found that detailed planning and optimization of the building process, following the Lean Construction Principles, are essential utensils to successfully introduce such new techniques.

Main findings of a full scale case study, “the Industrialized Concrete Bridge”, are discussed. It was found that significant manpower reductions, improved working environment and higher quality of final result were facilitated by increasing the degree of industrialisation. The success was, to some extent, dependent on how criteria of SCC were defined and how the concrete properties - and their variation - fulfilled the criteria. Thus, discussion is given on the optimization of robust SCC mixes and test results both from laboratory and building site.

1. INDUSTRIALISATION AND LEAN CONSTRUCTION

The productivity of the building sector has been low when compared to other sectors, e.g. the manufacturing industry. Industrialization is often mentioned as the measure to be taken and its definition is frequently debated in literature. To reach an industrial process, it is a common view that focus cannot only be on the production apparatus. The whole process from project idea to completed building needs to be controlled. Other important issues that must be addressed are logistics, collaboration between partners, standardized concepts, pre-manufactured highly processed components and information technology as well as Lean Construction philosophies [1], [2]. Now, strong efforts are taken by contractors towards industrialisation and for the concrete trade it is a question of survival to join this development.

At the industrialisation of cast in place concrete construction focus should be on, (Fig 1):
- Improved concrete qualities and optimal construction e.g. SCC.
- Minimized reinforcement activities on site (e.g. fiber and prefabricated reinforcement)
- Permanent and/or optimised formwork minimizing site logistics.
- Optimised concrete transport on site from the truck to form, e.g. pumping techniques;
- Weather independent construction processes, e.g. with climate protective tent; and
- IT and Lean Construction where multi-disciplinary decision makings are made at design, production planning, and construction e.g. reducing the “muda” [3], [4].
Not until nearly all of these six technologies are applied simultaneously, the distinct step into an industrialized process will be taken [3]. Working environment must also be addressed.

Figure 1: a) Industrial site cast construction by integrating material and production techniques with IT and Lean Construction [3], [4] b) Theoretical on-site time savings when applying industrial construction on bridge projects in Sweden c) Carpet reinforcement for bridge deck.

2. THE INDUSTRIALIZED CONCRETE BRIDGE

The project was initiated by following up traditionally constructed in-situ cast concrete bridges, in order to identify areas where major advancements in production could be achieved. Reinforcement, formwork and in-situ casting of concrete typically make up for approximately 50 % of the total construction time with relative ratios of approximately 1/3. The other 50 % of the time is needed for general establishment at the building site, foundation, pile driving, asphaltaling, railing etc. From a theoretical viewpoint, the implementation of industrialised construction methods would reduce the manpower substantially (Fig 1 b). For instance, when prefabricated reinforcement is used in the foundations and superstructure, the on-site construction time can be reduced with up to 80 %. A corresponding time reduction of 80 % could also be achieved if permanent formwork solutions are adopted. It should be emphasised that full benefit of course calls for detailed design and planning of logistics before construction can commence.

Main advantages of applying SCC are that casting rates are increased and that the number of workers needed for casting the concrete can be reduced. Theoretically, only one person is needed during the concrete casting (the concrete pump operator).

The studied full scale “industrial concrete bridge” was rather small, with a span of 10 metres and a width of 15 metres. A key for the success was that the owner, contractor, material supplier and designer cooperated during the complete project. Already during the design phase decisions were made in understanding between the partners that SCC and
prefabricated reinforcement for the foundations and for some of the superstructure should be used. It was also decided that carpet reinforcement (Fig 1c) were to be used for the bridge deck and that Lean Construction principles should be utilized during both design and construction phases. Left formwork was excluded from this case.

By using prefabricated reinforcement, the actual on-site production time were reduced to 6 hours from a planned on site fixing time of traditional reinforcement of 6 days. Thus, the first foundation could be cast on the afternoon the very same day i.e. at a time when the concrete plant normally has a low production engagement.

The average fixing time for carpet reinforcement in the bridge deck was 50 min/ton, which should be compared with at least 4 hours per ton, possibly more, for traditional net reinforcement. In total it was found that some 75 % of the on site assembly time for the superstructure reinforcement could be saved. The price for the material went up with roughly 50 % however, but since the cost for the assembly decreased by almost 90 % the overall economy was positively affected.

Using SCC on the bridge saved approximately 65% of the casting time as the number of workers involved was reduced. Examples of results from SCC castings are shown in Fig 2.

3. WORKABILITY & RHEOLOGY CRITERIA

Crucial for the success of SCC is to define the performance of the product, which can, according to the Growth project Testing-SCC [5], be discerned into three main parameters: 1) Filling ability, 2) Passing ability and 3) Segregation proneness. For these parameters, criteria should be established to be met by a proper mix design depending on geometry of structure to be cast, reinforcement, form type and, last but not least, method and local tradition on how to pour the concrete. Even though frameworks for such criteria have been established recently (e.g. ERMCO European Guidelines), specifications are rare in today’s construction with SCC. Experienced concrete workers have a clear understanding of optimum concrete, but this experience is seldom transformed into recordable parameters. Fig 2b shows possible target values and allowed variations of the filling ability, expressed by slump flow and T50, for wall and slab, where the areas represent the tolerances [4].

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horizontal and vertical bridge structures used at some occasions in Sweden. Criteria on passing ability and segregation proneness can, of course, be treated in a similar way.

The flowability can be expressed in the workability diagram (slump flow vs. T50) or more physically, in the rheology diagram (shear stress vs. viscosity). However, important is to clarify the possible relation between these parameters, see e.g. [4], [5].

4. OPTIMISATION METHOD FOR ROBUST SCC

The variation of SCC properties when delivered on site depends on a large number of factors such as fluctuations of properties of the concrete constituents, mixing procedure and transport conditions. In order to meet the criteria discussed above a robust concrete mix must be able to maintain its intended properties even though such parameters vary. To develop such a robust concrete mix is as important for a successful result as it is complex to accomplish. It is strongly believed that both theoretical analysis and laboratory tests on cement paste, mortar and/or concrete are required in order to develop robust mixes.

One theoretical approach available for the design of robust concrete is packing models, in which the packing ratio of the aggregates is considered. Several mix design methods for SCC are based on packing [4]. An example is the program 4C- packing, which utilizes a packing model based on spherical particles (a strong simplification). The results can be visualized in ternary diagrams describing the robustness when aggregate is varied (grading, particle shape etc.), Fig 3 [6]. The rheology behaviour of the fine (and “medium” fine) particles and cement paste must however always be optimized in laboratory tests and its properties i.e. the flowability and segregating proneness can be controlled by additives etc.

A Swedish research project is focused on robustness of the concrete immediately after mixing and specially the influences of aggregate and filler. The background is that in Sweden, due to environmental issues, an important challenge is to replace natural sand by crushed rock. Hence it is suspected that fluctuations in aggregate grading and moisture will increase.

Fig 4a shows typical influences of humidity variation of sand, not compensated for, when natural aggregate is replaced by crushed rock. It is evident that the crushed rock, particularly at a total replacement (KK), implies a more sensitive system with respect to water variations. Increasing the cement content or paste volume, often done in reality, seems to be effective measures to enhance the robustness for SCC with crushed aggregates, see Fig 4b. This is however costly and can lead to negative effects, like increased shrinkage and heat generation.

5. EXAMPLE –FULL SCALE VS LABORATORY TESTS

Fig 2 showed that the SCC for the bridge deck did not completely meet the criteria set up by the client. Out of 23 documented deliveries 5 displayed too low slump flow or too high T50. Hence, the robustness of the recipe was examined in a small laboratory series where the aggregate sieve curve was varied (reference, fine and coarse, Fig 3b)) and the humidity was varied from -1 % to + 1 % (without compensating for it at mixing). Moreover, some tests included a change in filler content from 120 kg/m³ (reference) to 80 and 160 kg/m³.

The results (Fig 5) indicated that the actual mix was relatively robust. However, it is evident that, to fulfil the criteria set up (SF of 720 ± 20 mm and T50 of 3,5 ± 1 s), the SCC could not withstand a humidity change of ± 1 %. For example, the reference mix (the same
Figure 3: a) Ternary diagram with packing degree from 4C-packing and tests for different combinations of three crushed aggregate fractions. Packing degrees when aggregate is varied can be studied [6]. b) Variation of grading 0/8 mm used in tests of Fig 4.

Figure 4: a) Workability when 0/8 and 8/16 natural aggregate (NN) are replaced by crushed rock (NK, KN and KK). b) Shear stress (ConTec 3) for SCC with crushed aggregate when cement content is increased. Moist = +0,5% moisture of sand, dry = -0,5%) [4].

as delivered on site) displayed a slump flow of 580 mm at -1 % humidity change, i.e. out of the range, and considering T50, it can be seen that a problem arises for the wet mix (+ 1 %). The influence of grading curve is somewhat conflicting. Coarser and finer curves resulted in too low slump flow as compared to the criterion. Regarding T50, it can be seen that finer grading curve may give acceptable results while coarser did not. Somewhat surprisingly, the robustness in regard to moisture variations seems to be better with a coarser grading curve. It should also be mentioned that the V-funnel and the rheology tests followed the same tendencies as obtained in the slump flow tests. Thus, it seems that, for this mix, some relationships exist between the test methods.
6. CONCLUSIONS

Major efforts are now taken by contractors to increase the degree of industrialisation of the building process and it is of utmost importance for the concrete trade to join this development. Crucial for the development is to integrate material- and production techniques with information technology. A robust self-compacting concrete is here a significant component.

Theoretical models based on e.g. the packing theory are efficient tools to study the robustness of SCC when aggregate related parameters vary serving as one input for the mix optimisation. The packing studies must however always be combined with laboratory tests on cement paste, mortar and/or concrete. Furthermore, it is important to define clear and recordable criteria for SCC expressed in workability parameters and/or rheology parameters.

REFERENCES