Industrial concrete construction for a better economy and working environment – possibilities and obstacles with self compacting concrete

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ABSTRACT
The implementation of SCC together with new reinforcement and form techniques make it possible to increase the degree of industrialisation. It has been found in research at LTU that detailed planning and optimization of the building process, are essential utensils to successfully introduce such new techniques.
However, also important is to address the technical issues hindering the marketing of SCC. Such issues are the robustness of the concrete and he surface quality. Thus, a discussion is given in the article on the optimization of robust SCC mixes and test results both from laboratory and building site as well as how criteria of SCC can be defined.

Key words: Cast in place concrete, industrialization, self compacting concrete, productivity, economy, robust SCC, mix design, aggregate packing

1 INTRODUCTION

In the late 1990´s it was expected SCC to have more than 50 % of the total concrete market within a five year period, but what happened with the foreseen development? Today, almost ten years later, the market share of SCC in EU nations generally is as small as 1 % (at 2006 according to European Ready Mixed Association, ERMCO) with large variations; e. g. about 2 % in France & Norway, 1 % in Finland, Netherlands & UK and 5 % in Sweden while, on the other hand, the SCC market share in Denmark is as high as 28 %.

An important reason for the low use of SCC is the economy. The need for high quality concrete constituents results in a more expensive product that, according to the general opinion of end-users, not compensates for possible economical benefits. It is also known that several technical issues hinder the introduction of SCC on a broader front like questions regarding the *formwork pressure*, problems related to static and dynamic *segregation resistance*, rapid *loss of slump flow* and doubtful *robustness*, unaccepted *surface quality*, insufficient *accuracy of production equipment*, *quality control* requirements and a *lack of standards* (see e. g. Shah et al. [1] and Cussigh [2]).

The challenges increasing the share of SCC in RMC (ready mixed concrete) construction in general are closely related to solve the abovementioned problems as well as to clearly document and convince the market on all the direct and indirect benefits using SCC. An overview of some selected issues is given in the paper as well as examples from research and case studies.

The success of SCC in Denmark may be commented on. In Denmark the application of SCC started almost from a zero level at 2000. With support of a large national R&D project ("The SCC consortium", 17 industrial and research institute partners), and certain strategies for initializing and promoting the SCC products, the SCC level increased to about 400 000 m^3 at 2003 and 800 000 m^3 at 2006, i. e. a 30 % share of RMC [25] in the country.

2 THE PERFORMANCE OF SCC – CRITERIA AND ROBUSTNESS

2.1 Criteria

The lack of robustness and quality assurance system for difficult castings (e. g. narrow structural section and dense reinforcement) are considered to be important obstacles when marketing SCC. Robustness is related to the performance of the product, which can, according to the EU Growth project Testing-SCC [3], [4] be discerned into three main parameters: 1) *Filling ability* 2) *Passing ability* and 3) *Segregation proneness*. For these parameters, criteria should be established depending on geometry of structure to be cast, form type, reinforcement, and, last but not least, method and local tradition on how to pour the concrete. Figure 1 shows possible target values and allowed variations of the *filling ability* (slump flow and T50) for horizontal and vertical bridge structural elements used at some occasions in Sweden. The diagram can be transformed into a corresponding rheology diagram; i. e. slump flow and T50 are related to shear stress and viscosity respectively [4]. It is seen that, for a proper form filling, the concrete for a bridge deck should have slightly less fluid properties as compared to a wall concrete. Criteria on *passing ability* and *segregation proneness* can, of course, be treated in a similar way.

Furthermore, Walraven [6] concludes that SCC can be tailor-made for any kind of construction and suggests nine consistency classes described by slump flow, T50, V-funnel time, passing ability and segregation properties. The consistency classes are dependent on the construction part (e. g. walls, floors) and have been approved in EU SCC guidelines [7], Figure 2.

In Denmark, main applications are horizontal castings (slab on grade, industrial floors and foundations), i. e. fairly uncomplicated geometries and reinforcements [25]- [27] . Therefore, the Danish SCC feature a rather moderated flowability; slump flow in the range of 500 – 600 mm, mainly in order to avoid segregation, i. e. properties rather different the ones of Figures 1 and 3.

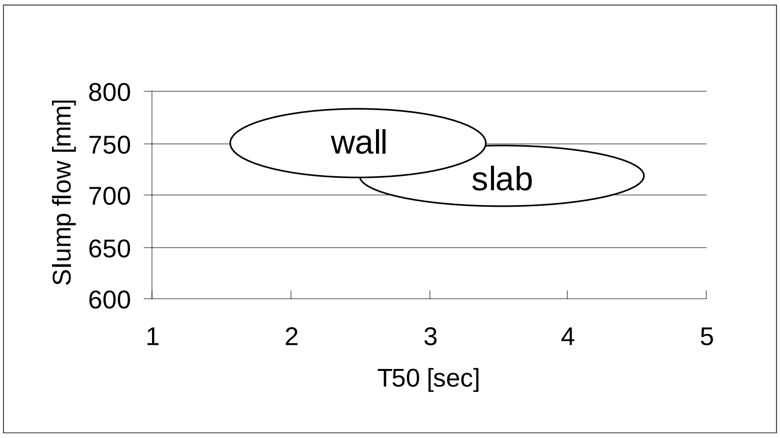


Figure 1 Examples of target values in slump flow - T50 diagram for SCC, wall and slab (here bridge deck), where the areas in the diagram represent the tolerances. Transformation of slump flow into shear stress and T50 into viscosity gives corresponding rheology target values [4],[5].

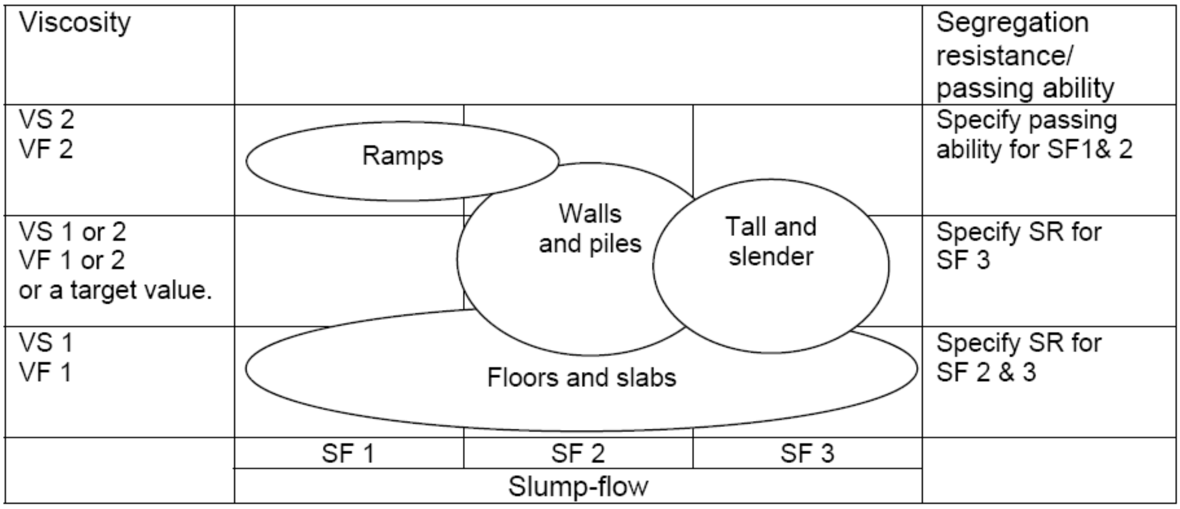


Figure 2 Properties of SCC for various types of application suggested in EU guidelines of SCC [7] based on [6], VS, VF – viscosity classes obtained by T50 or V-funnel respectively. SF-slump flow classes, SR – segregation resistance.

Criteria for all SCC-casting should be defined by the contractor, to be met by a robust SCC that is controlled by an agreed quality assurance system (by testing at building site and/or concrete plant). Examples of results from such a SCC site testing are shown in Figure 3.

Concerning the quality assurance system, crucial is to document reliable values at the plant or site testing, which focus on the precision of test methods chosen. According to the Growth EU project Testing SCC, precision consists of two elements – repeatability and reproducibility which thus are statistical measures of the error inherent in a test method [3] [4]. The first measures is the likely error of tests on identical material performed by a single operator, and the second that of tests performed by different operators also on identical material. It is necessary to know the magnitude of these errors in order to properly understand and interpret test results and to establish the tolerances of SCC criteria.

Within the project Testing SCC, a comprehensive inter-laboratory study was performed establishing precisions of the most common test methods for SCC, see [4]. For example, slump flow and T50 test methods implied precisions according to Table 1. It was observed almost no significant difference between repeatability and reproducibility, indicating that the operator (or within-laboratory) variance dominated the precision. Rather large values of precision are observed and, hence, it is concluded that acceptable tolerances of SCC criteria not imply too narrow limits.

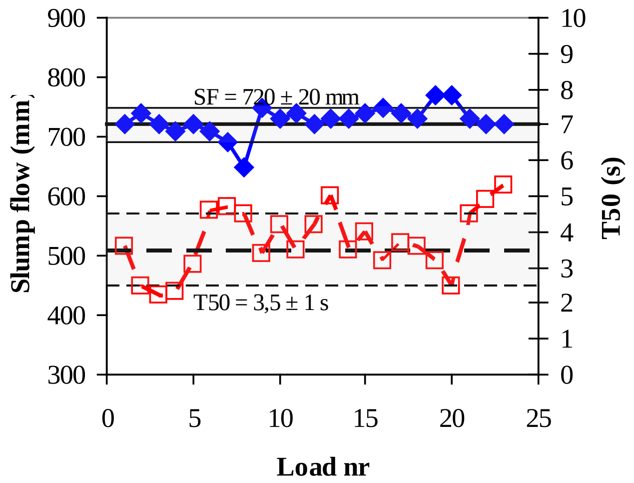


Figure 3 Slump flow (solid dots) and T50 tests at bridge deck casting meeting target values of Figure 1 [5].

Table 1. Precision of slump flow and T50 expressed in reproducibility obtained at an inter-laboratory study within the Growth EU project Testing SCC [3], [4].

Test method	Range	Reproducibility
Slump flow	SF: 600 – 750 mm	43 mm
	SF: > 750 mm	28 mm
T50	≤ 3,5 sec	0,88 sec
	3,5 – 6 sec	1,18 sec

2.2 Robustness

Generally speaking, *robustness* is defined as insensitive against disturbance [8] and for SCC the disturbance appears in the form of fluctuations of the concrete constituents properties, mixing procedure and transport conditions. An important feature of SCC is thus the ability of the concrete to maintain its fresh properties and structure during transport and casting of a single batch or multiple batches, [5], [9].

To develop a robust concrete mix is as important for a successful result as it is complex to accomplish. It is believed that *both* theoretical analysis (by e. g. packing theories) *and* laboratory tests on cement paste, mortar and/or concrete are required in order to design reliable mixes [5]. In Sweden it is now striven to establish such a mix design system for SCC, considering e. g. the aggregate fluctuations.

The SCC should thus allow for certain variations of influencing variables. For the properties of the concrete immediately after mixing, variables like aggregate uneven grading and uneven humidity of aggregate as well as unequal qualities of constituents can be discerned. According to the European SCC guidelines [7] a well designed and robust SCC can typically tolerate a variation of 5 -10 liters/m^3 in mix water content which in practice is about 3 – 6 % of the total water content per m^3. This variation corresponds to a 0,5 – 1,0 % humidity variation of the sand fraction (0 – 8 mm), a level of sudden changes in moisture that can be handled at the concrete production in Sweden.

2.3 Examples of activities studying the robustness of SCC

Ongoing projects in Sweden address the robustness. One project reflects the influences of aggregate and filler on the variation of SCC properties. The reason is that an important challenge is to abandon the natural sand as main aggregate type entirely using crushed aggregate instead. In order to fulfil demands from the society regarding more sustainable environment, the use of natural gravel must be considerably reduced or even stopped in the nearest future. Crushed rock is the only alternative implying that proportioning tools must be further developed to consider the certain feature of the crushed rock – and variation of it. In the project, main variables to be examined have been identified to: aggregate type (natural, crushed), aggregate grading and distribution of particle shape, humidity of the sand and effects of industrial or natural filler.

Figure 4 shows typical influences of humidity variation of sand (+/- 1 %), <u>not compensated for</u>, when natural aggregate is replaced by crushed rock [10]. It is evident that the crushed rock, especially at a total replacement (KK in the figure), implies a more sensitive system i. e. the robustness is much lower than for natural aggregate (NN). Increasing the cement content or paste volume seems to be one effective measure to enhance the robustness for crushed aggregate concretes when varying the water content, see Figure 5. This is often done in reality but is however costly and implies negative effects like high shrinkage, high temperature increase and cracking as well as a negative environmental impact – important in the climate debate of today.

As known, several other methods are available increasing the robustness of the concrete. For example, viscosity agents and industrial filler often imply a more water insensitive system. Ongoing research at e. g. CBI in cooperation with the University of Sherbrook shows promising attempts of developing a variation stabile concrete.

Figures 6 and 7 depict tests results for variations of Civil Engineering SCC mix properties (different aggregate grading, filler content and cement paste content) when water content were varied similarly to Figs 4 and 5. The impact of filler content and grading curve is clear. Some influence of mix on robustness was detected.

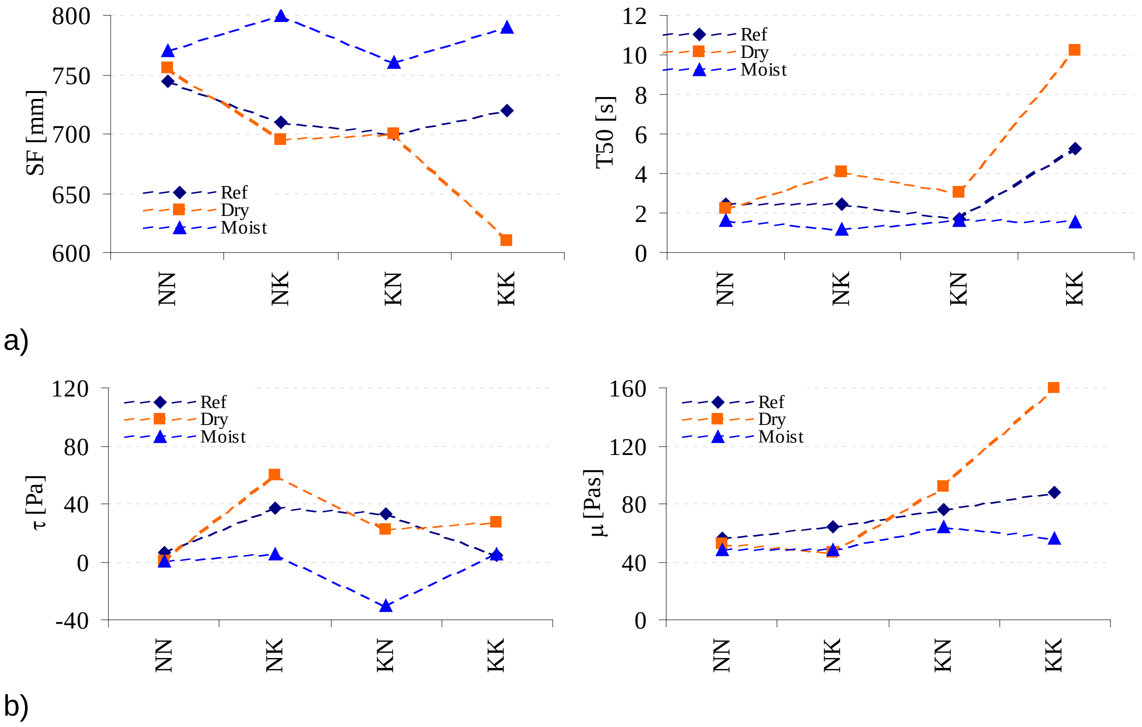


Figure 4. Slump flow and T50 (a) and shear stress and viscosity (b) when 0–8 mm and 8–16 mm natural aggregates (NN) are replaced by crushed 8-16 mm (NK), crushed 0-8 mm (KN) and at a total replacement (KK). Moist = + 0,5% humidity of sand, dry = - 0,5%) from reference sand moisture without compensation, cement: Std Portland Type II, 42,5 A-LL (Byggcement, Cementa) 350 kg/m^3, w/C = 0,5, [10] Rheology testing by ConTec 3 viscometer [22]

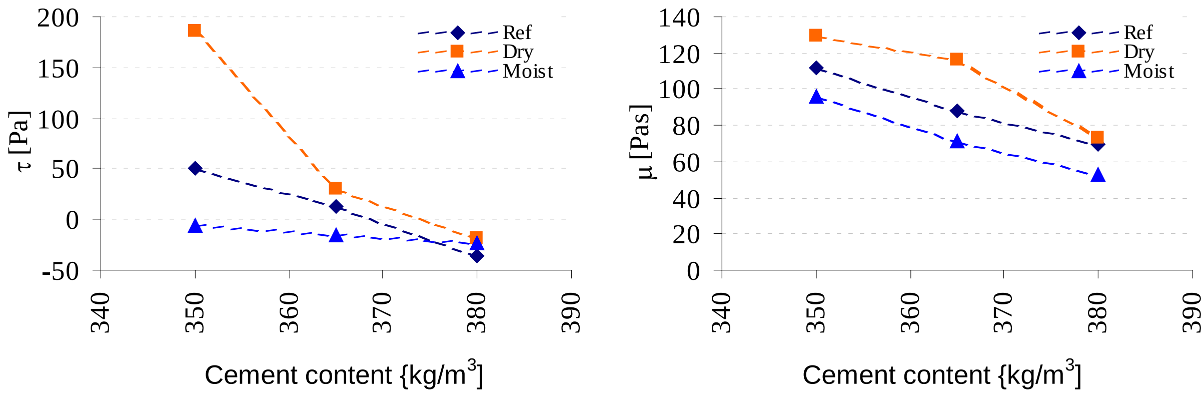


Figure 5. Shear stress, τ, and viscosity, μ, (ConTec 3 viscometer [22]) for SCC with entirely crushed aggregate for an increase of cement content. Moist = +0,5% moisture of sand, dry =-0,5%), (see also Figure 4) [10].

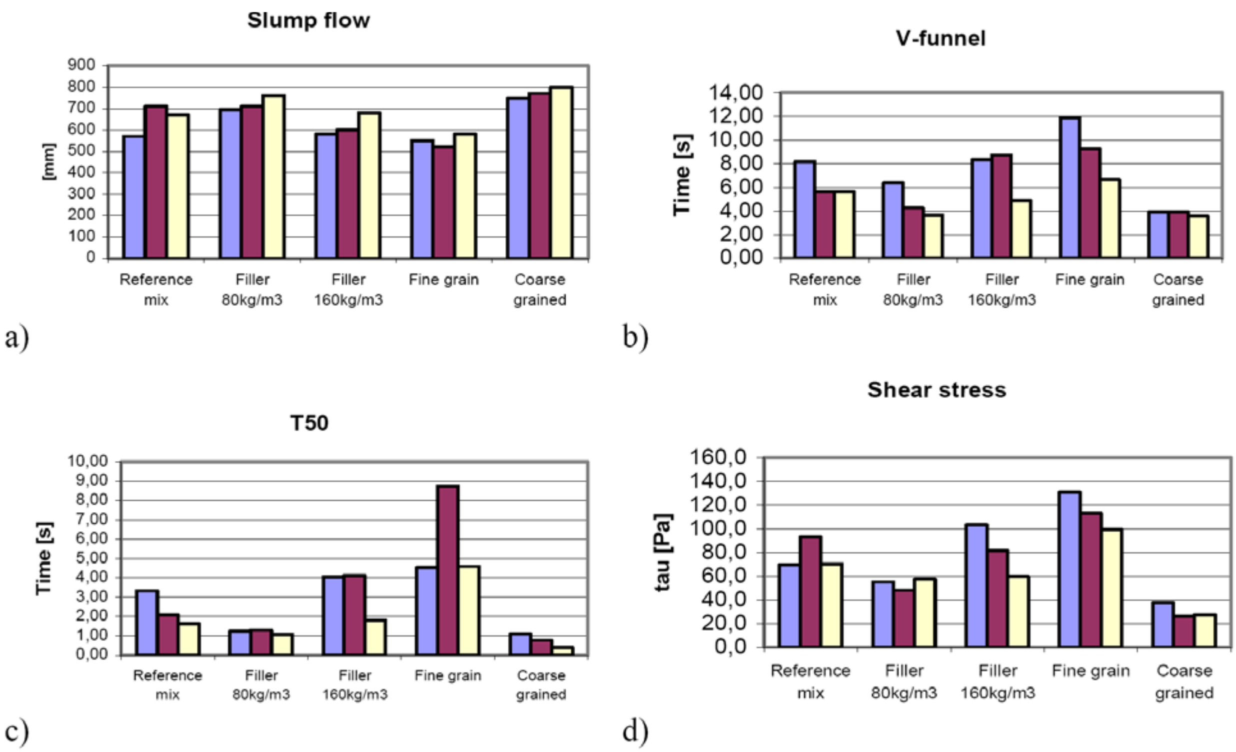


Figure 6. Example of influences on workability (slump flow, V-funnel flow time, T50) and rheology (shear stress, τ) of moisture variations of fine aggregate (left: +1 %, middle: reference moisture, right: - 1 %). Laboratory tests with concrete used at the full scale bridge casting of Section 5, variations of filler content and grading curve. Cement: Std Portland Type I, 42,5 N MH/SR/LA (Degerhamn, Cementa), 450 kg/m^3, w/C=0,40, reference limestone filler content: 120 kg/m^3, from [11].

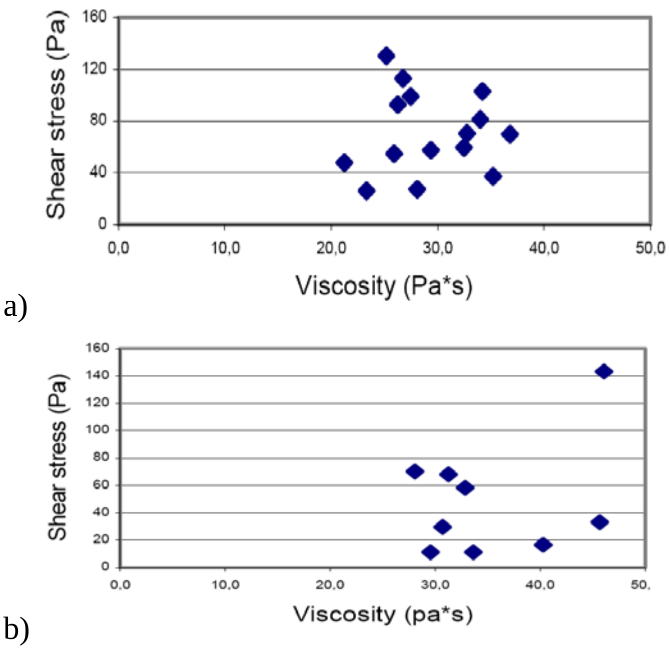


Figure 7. Example of influences on rheology (shear stress and viscosity) for fine aggregate moisture variations. Tests with different lime stone filler content and grading curve, (see Fig 6), (a) and (b) represent different concrete mixes made with the same aggregate [11].

3 METHODS TO DESIGN A ROBUST SCC

It is clear that the design of SCC shall fulfil various types of target values that, in fact, can imply contradictory strategies in material optimization. Therefore, it is important to carefully check with the client and the contractor the overall set of criteria, both as written "on the drawings" but also regarding casting conditions etc. (This is nothing new in this matter but the question has become more critical with SCC). It is thus important that the tolerances of the criteria are defined (the size of the area in the workability/rheology diagrams, Figure 1) which is met by a certain robustness of the material.

One philosophy regarding mix design of SCC is to consider the air voids of the aggregate. For an optimum flow, the air void volume of a certain fraction when packed should be filled by finer fractions of the material - and somewhat more i. e. an excess of finer particles is established. Similar conditions are valid for the finer fractions and the filling of the air voids of each fraction, achieving an optimum mobility, is repeated down to the smallest filler ending up by obtaining an excess of the cement paste volume. A correct mix of aggregate fractions thus gives the optimum grading curve and volume of cement paste. The rheology behaviour of the cement paste defines parameters like flowability and segregating proneness and can be controlled by superplasticiser, viscosity agent, cement and fine grained filler etc.

It is however observed that, in reality, for a concrete producer, the aggregate is often given i. e. one sand and one stone fraction is at disposal.

Several mix design methods of SCC utilize the theory above (see e. g. [13] – [18]) like the early proportioning system [13] where the coarse aggregate volume was fixed at 50 % of its packing density (50 % void volume). The properties of the mortar were adjusted in order to provide significant viscosity and flowability. The early excess paste theory explained the fact, to attaining workability, it is necessary to not only cover the surface of the aggregate with cement paste to reduce the friction but also to add more "excess" paste. The theory has been further developed to SCC by several researchers [14] [15]. At LCPC, France, a more refined method was developed based on the Compressive Packing Model (CPM) in which it is possible to consider grading and particle shape of each fraction more generally and to optimize the overall particle size distribution [16], [17].

Input to the CPM and other packing based models is the aggregate packing, see Figure 8, showing results from packing tests (loose packing i. e. not exposed to vibration) on fractions of 0,125 – 2 mm materials. Clear differences between natural and crushed aggregate are shown.
Pilot calculations have been performed earlier [10] with the SCC-mix software based on the Compressive Packing Model [17] that was one output of the Brite-Euram project SCC [18].
Mainly, the influence of aggregate was studied by replacing natural aggregate with crushed similarly to the tests of Figures 4 and 5, see Figure 9. Except values in wrong level with regard to rheology (i. e. the values should be lower) due to insufficient calibration of superplasticiser influence in the program, the trends are logic and the agreements with test results are markedly good. With crushed rock and 380 kg/m^3 cement, about the same flowability was achieved as with natural aggregate, both theoretically (shear stress and viscosity) and at tests (slump flow tests), see Figure 9.

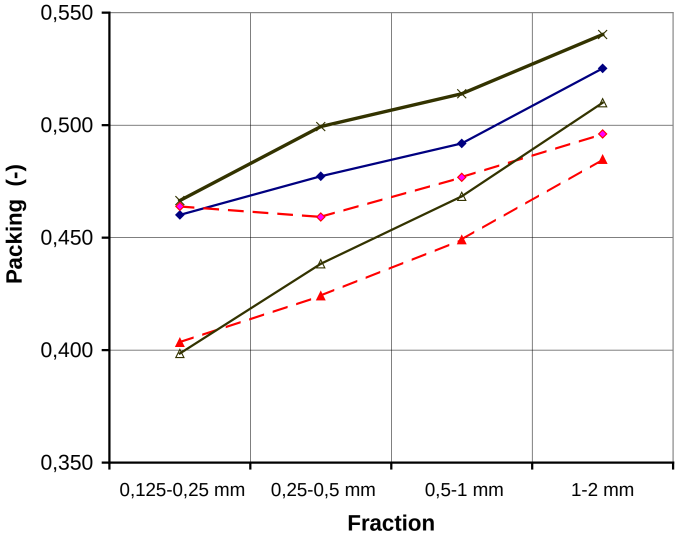
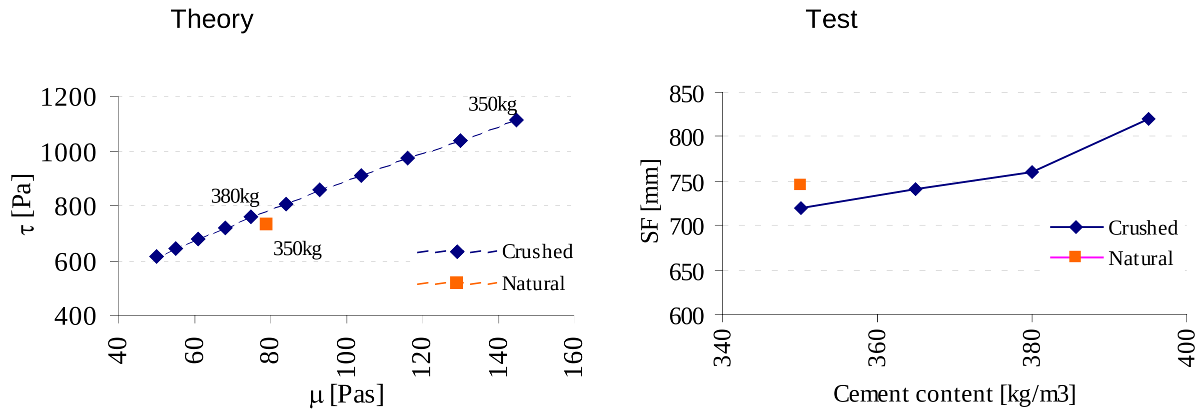


Figure 8. Packing densities documented for four fractions of one natural (thick solid line) and two crushed aggregates (dashed line) as well as two crushed aggregate treated to achieve a more cubic particle shape (thin solid) (tests at RMC company Betongindustri, local aggregates Stockholm)

Furthermore, Figure 10 shows the robustness for moisture changes of sand without compensation for natural and crushed aggregate, with calculated values by the SCC-mix software. The positive influence on robustness is demonstrated when adjusting the sieve curve of crushed aggregate to be similar to the one of the natural aggregate.

The mix design system for normal vibrated concrete and SCC, that is now to be developed in Sweden, will to some extent use the packing theories. This seems to be a promising approach as shown by the pilot calculations of Figs 9 and 10.



a) b)

Figure 9a) Influence of cement content on rheology parameters (theoretically calculations with the Compressive Packing Model) and b) slump flow tests. Natural and crushed aggregate. In the calculations, the cement content was increased from 350 kg/m^3 to C ≈ 380 kg/m^3 for the concrete with crushed aggregate to obtain same shear stress (i. e. flowability) as natural aggregate. This was similar to the behaviour at the workability slump flow test [10].

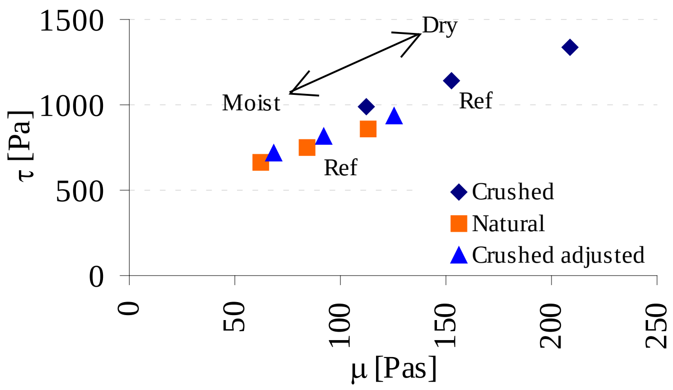


Figure 10. Rheology parameters as calculated with SCC-mix program [17] for crushed and natural aggregates at moisture changes of sand. Moist = +0,5% moisture of sand, dry =- 0,5% (see Figure 4). Calculations were also performed when crushed aggregate curve was adjusted to be exactly the same as the one of the natural aggregate [10].

4 SURFACE QUALITY

Initially, at the introduction of SCC, the concrete was marketed to give perfect surfaces, free of pores or other defects. As known, despite some very successful cases (e. g. Figure 11), this target has rather seldom been achieved during the ten years of SCC use and several investigations have been initiated to examine the reasons of the absence of excellent surfaces.

If the SCC meets the three criteria of filling ability, passing ability and stability, it is assumed that it is possible to produce homogenous structural elements with high quality surfaces [19]. However, like the case with ordinary vibrated concrete, the surface of a SCC structure, in addition to the concrete material as such, also is influenced by the (surface) quality of the form, the form releasing agent, the way of casting, filling rate, weather condition and more. A perfect

Figure 11. Perfect concrete (also inward) surfaces without pores or any other defects of a Swedish bridge cast 1999 with high performance SCC.

surface cannot be guaranteed unless the concrete fulfils the three criteria. But the defects, which can be subdivided into air pores, water pores and inward bends, can be mitigated.

Moreover, often, the source of a surface failure can be explained in a sudden inadequate delivery, which according to above, can be related to a low robustness of the concrete.

In Gram [19] and Emborg [20] some recent findings are found on the surface defects and how to avoid them. It can also be mentioned that several projects have been started in the Nordic countries to optimize concrete for perfect surfaces and to recommend practical measures to avoid the defects.

5 PRODUCTIVITY AND ECONOMY

One of the drawbacks with SCC is, as mentioned above, its high prize due to the quality demands on the concrete constituents and higher manufacturing costs. Hence, it is important to make SCC profitable also for the end user i. e. the contractor, which means that the construction system needs to be adapted to the “new” concrete, by that increasing the productivity.

Although several “technical” benefits of SCC can be expected, e. g, increased durability and strength, implying lower future maintenance cost and possible reduction of shear force reinforcement as well as structural cross sections, it is the productivity related gains that are of importance. Today, contractors however usually do not take these benefits into consideration. Instead, when casting SCC they use the same casting methods and amount of workers as with traditional vibrated concrete resulting in “normal” productivity and a poor production economy as the material costs and initial costs are higher. Fortunately, some exceptions from this are present in the Nordic countries.

One example is demonstrated in a PhD research project, “Industrialized Construction of RMC Bridges” [11]. SCC has been combined with effective reinforcement mounting (prefabricated cage reinforcement for foundations and carpet rolled reinforcement for bridge deck) as well as with production planning according to so called Lean Construction Philosophies [12], [21].

Two examples of full scale bridges were included in the study. Cost assessments clearly demonstrate the economical potential using SCC, especially if on-site man-power is reorganized. Marked reductions of man-power were obtained for e. g. the superstructures of the bridges using SCC. The total concrete costs for the superstructure (including the higher prize of the concrete) were equal or below the estimated costs if traditional concrete had been used. If reorganization of concrete workers had been accomplished (e. g. by means of two casting teams instead of one at the second case) the reductions would have been even larger i. e. the man-power need was considerably less the ones for a traditional casting,

6 WORKING ENVIRONMENT AND RELATED COSTS

Although the Swedish construction working environment is regarded as on of the safest in the world on the subject of physical health, working conditions, illnesses and accidents, still working environment related health problems exist that needs to be tackled [23]. Regarding concrete workers, 279 cases of Work-related Muscular Skeletal Disorders (WMSDs) were reported in Sweden 2004 and their sick leave compensations was estimated up to *1,3 millions €*

for the taxpayers. It is noted that this is valid for Sweden with, as compared to other EU nation, a small consumption of RMC per capita (resulting in 3 million m^3 per year in total). For ERMCO nations (European Ready Mixed Organisation), if the working environment is assumed to be equal to that of Sweden, the number could be extrapolated to *214 millions € for the EU taxpayers* (492 millions m^3 of total annual RMC production). Moreover, for the contractors, of course other direct and indirect costs than sick leave compensation exists such as productivity loss and hiring substitute workers, probably *equal or higher* than the numbers above, which should be included in the injury cost estimations.

According to a study at the Danish Technological University [24] some 26 % of a workers average day consists of concrete casting and reinforcement fixing - a work that often is done in awkward postures with heavy equipment such as the poker vibrators for the traditional concrete or with heavy material when placing the reinforcement piece by piece. It is argued by the author of [24] that construction workers is one of the most exposed groups of employees in the society today when it comes to noise level, heavy lifts, poor ergonomics and varying weather conditions. The difference in working environment between traditional casting of concrete and casting SCC has been debated in recent publishing, and all argues for the importance of introducing SCC for the workers point of view. Unfortunately, there are few investigations which actually grade the working environment when casting traditional concrete as compared to SCC. One interesting example is however presented in the above mentioned PhD research project, [11], [12], [21].

Pilot studies were performed using the so called ErgoSAM and Cube models on site observations to acquire the risk of abovementioned WMSDs. At one of the full scale studies in the project, a mean value of work cycle load exposure level was documented and compared with the use of traditional vibrated concrete. Very large load exposure level reductions were obtained; the exposure level was in general about 1/3 as compared with casting of traditional vibrated concrete.
It was concluded that the effect of SCC on working environment is fundamental, constituting a base for strong economical benefits both for the society and, in fact, also for the building industry that cannot only concern about the short term site related benefits.

7 SUMMARY AND CONCLUSIONS

Besides solving technical problems, the possibility of increasing the market share of SCC is closely related to how <u>all</u> the direct and indirect benefits using the concrete are demonstrated. The challenge of the concrete sector is to market these benefits!

In Swedish studies it has been observed that, when estimating productivity and costs, it is important to adapt the site organization to the potential of the SCC. With a smart production planning, large reductions in unit time and total project time can be achieved. Some 20 – 25 % reductions of unit and project times as well as costs have been realized in pilot full scale tests.

Moreover, long term benefits of SCC should be addressed and demonstrated i. e. by reducing the costs for sick leave and injury related to an unhealthy working environment. The important benefit on working environment observed when using SCC will be followed up by new site examinations. Unfortunately, the chance of improving the working environment often is denied in the Nordic countries as the contractor only considers the short term prize for material and man power and not the total possible long gain from e.g. the enhanced working environment. This attitude must be changed!

Of course, the technical obstacles hindering the marketing of SCC also should be directed in future actions. Activities are now focused on establishing criteria for the SCC on site, designing robust concrete mixes (using e. g. packing theories) meeting the criteria and finding a proper quality assurance system documenting the concrete delivered. When establishing criteria, important is to take into consideration the maximum precision of test method chosen as defined by e. g. the EU Growth project Testing SCC.

Although concrete manufacturers in recent time have improved the quality and hence the robustness of SCC, still deviations are present with the negative influence that the contractor calculates the risk when using SCC to be too high. Therefore, often the contractors simply *do not use the product even though both costs and time evidently can be saved*. Hence, the casting at site is performed with no reductions in man-power to be on the safe side, i. e. no large benefits in productivity are achieved.

If it is intended to increase the market of SCC, also the phenomena beyond the surface defects must be understood and reliable concrete mixes for perfect surfaces as well as casting methods in conjunction with form qualities should be established and documented in guidelines.

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