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# Development of Self-Compacting Eco-Concrete


## Abstract

Ever since its introduction and increasingly widespread use since the early nineties, new mix design methods of Self-Compacting Concrete (SCC) can hardly be recognized. Despite intensive research and a substantial number of publications in this new technology the design concept still mainly follows the so-called "Japanese method" introduced by Okamura /17/. More recently, Su and Miao /19/ and Su et al. /20/ developed an alternative method for composing SCC. This method was further improved by Brouwers and Radix /5/, which is the starting point of this study.

This new approach for the mix design is primarily based on the grading of all involved solids as well as on the exact knowledge of the water demand for sufficient flowing. Theory and experiments regarding this method will be explained. In this context, the cement efficiency, as an outstanding measure for the evaluation of strength properties, is also applied. Finally, the results of hardened concrete properties are documented, which proves the significance of this design method as a tool for the production of competitive self-compacting and ecologically friendly concrete mixes.


## Introduction

The prefix "Eco" for the material concrete itself is partly redundant since concrete is produced from cement the main components of which are lime, clay and minerals, and aggregates of various grading which are taken from nature. To some extent industrial waste products (e.g. slag or fly ash) or recycled materials are used as filler or aggregate as well. In addition surplus material of fresh concrete is reused and hardened concrete also can be used as an aggregate after crushing. This already shows a contribution toward the protection of the environment, even if the reasons in most cases are economical. However, in view of an increasing ecological and environmental awareness we should define the term "eco" in a much broader sense.

In this context the optimization of packing and custom-tailored grading (particle size engineering) leads to strong and dense grain skeletons which no longer require high amounts of cements for appropriate strength and durability characteristics. Another consequence of high packing density is a reduction of the water demand since less void volume has to be filled with water and therefore lower water/cement ratios can be realized. Self-Compacting Concrete (powder and combination type) with its high cement content is particularly interesting for this field of research. SCCs with low cement contents do not only represent cheaper and thus more competitive mixes, they can also reduce the environmental impact to an important extent. Lower quantities of cement also mean reduced $CO_2$-emission during cement production. Furthermore, if with a given amount of cement the strength can be increased due to optimization, it is also possible to reduce dimensions of constructional elements providing equal load capacity on the other hand. Reduced demand of material may result in less transportation of raw materials and ready mixed concrete (or prefab elements) and a lower water demand. Furthermore, the resources of pits and quarries needed for aggregate and binder production are treated with more care. This is an important factor since for environmental reasons many concessions for quarrying will not be renewed nor granted at all. In addition, in some countries there is already a lack of appropriate gravel. A shift from gravel to sand can be noticed in several quarries worldwide. This was already pronounced in the eighties /9/.

If these principles for cement reduction and higher performance concretes were considered and introduced in the construction industry, it would mean a major step forward with regard to environmental protection.

## Theory

For many years there has been already an awareness of the influence of the particle size distribution (governing both packing and internal specific surface area) on workability and hardened properties of concrete mixes, e.g. see the early work by Féret /10/, Fuller & Thompson /11/ and Furnas /13/. It is all the more remarkable that in literature there is hardly any indication to consider all solids in a concrete mix with regard to their grading.

Packing models, for continuous and discrete packing as well, are available in a significant number. In recent years, the role of powder materials became more and more important. Numerous publications confirm this. Especially in the field of Self-Compacting and High-Performance Concrete, extensive research has been carried out with a focus on particle packing. The Linear Packing Density Model (LPDM), the Solid Suspension Model (SSM) and the Compressive Packing Model (CPM) as a representative of the so-called third generation of packing models are well known examples for packing models /15/. For the most part of these models the amount of solids was cut into coarse and fine sections and optimized separately concerning their packing. A couple of research projects were focused on dense packing of cement or fine mortar pastes. This becomes essential when designing Ultra-High Performance Concretes (UHPC). The fine fractions and their packing are primarily responsible for complete porosity. An integral approach based on the particle size distribution of all contained compounds, however, can not be found that often. This led to the development of a mix design containing new ideas of particle packing.

For the description of continuously graded granular blends a lot of mathematical models are available. In the majority of cases the Fuller parabola is applied which represents the basic principle of most standard aggregate grading curves. Within this power law size distribution a fraction (by weight) finer than a given sieve size is computed by the following term:

$$F(d) = \left( \frac{d}{d_{max}} \right)^{0.5} \qquad (1)$$

where d is the sieve size and $d_{max}$ represents the maximum sieve size (i.e. where 100 % passing takes place). Given that the exponent of this power law distribution is fixed at 0.5 and no measure is applied concerning the smallest particles, this model lacks adaptability. Ignoring these parameters densest packing cannot be obtained. The introduction of a variable exponent q by Andreasen & Andersen /1/ and a minimum particle size $d_{min}$ by Funk & Dinger /12/ led to a better approach which reads as follows:

$$F(d) = \frac{d^q - d^q_{min}}{d^q_{max} - d^q_{min}} \qquad (2)$$

The exponent q which henceforth is denoted as distribution modulus allows controlling the character of the generated mix regarding its fineness of grain. Higher values of q create coarser mixes ($q \geq 0.5$) whereas smaller values lead to fines-rich granular blends. It is supposed that this distribution law delivers a handy tool in order to obtain dense packing (close to the optimum state). Furthermore, it is believed that decreasing values of q lead to better packing which theoretically yields an optimum packing at q in the range 0 to 0.28 /4/. Note that Eq. (2) turns into a logarithmic function of the particle size for the special case q = 0. Several researchers (/1/, /7/, /12/) refer to a distribution modulus of 0.37 for spatial grain distribution in order to obtain optimal packing and therefore minimum porosity.

Existing design methods for SCC assume that powder particles have to be covered with a water layer of a certain thickness and the coarse aggregates again have to be covered with a layer of mortar. The grading of this mortar is for the most part secondary. Its workability is controlled by high amounts of fines and the addition of highly effective plasticizers. Based on this separation of coarse and fine there are also limitations which have to be respected during composing a mix. That way, for instance the volumetric content of gravel in the total aggregate volume and the content of sand in the mortar volume are fixed a priori /3/. Applying Eq. (2) for the generation of a dry concrete mix makes such limitations unnecessary.

**Modeling**

Based on the theoretical conclusions stated above, a design model was created which is based on the grading as a whole. Thereby all included solid materials are considered – from the coarse aggregates up to the finest powders. By means of Eq. (2) a particle size distribution is formulated which serves as a target curve for the creation of the whole solid blend. The parameters $d_{max}$ and $d_{min}$ are defined by the coarsest and finest materials respectively and the distribution modulus can be freely selected. Within the framework of this research, several tests have shown that for the design of SCC a q in the range of 0.22 up to 0.40 is to be recommended. Higher values of q result in coarse mixes which are prone to segregation and blocking whereas smaller values of q deliver fines-rich granular blends which suffer from high apparent cohesion due to the high amount of fines and dense packing. These mixes are exceedingly difficult to handle concerning their workability. This behavior is known from UHPC. The interval of $0.30 < q < 0.35$ is of special interest since it seems to be the balanced state of both above mentioned extremes.

In order to obtain a concrete recipe from this basic distribution law, the instrument of linear optimization was used to create a granular blend which fits best to the target distribution /14/. The optimization target thereby is the smallest possible deviation between target curve and the generated blend of all raw materials. This deviation can be evaluated in different ways. It has been shown that the most practical way is the computation of the interval between both curves at fixed particle sizes using the method of least squares. In doing so, a uniform distribution of the selected particle sizes has to be guaranteed in order to prevent an overestimation of a specific fraction. For the present model a grading with an increment of factor √2 (diameter ratio of subsequent size groups) was applied. This factor was used for the characterization of all raw materials as well. In compliance with some additional regulations that can be embedded in form of constraints, the optimization process can be started. These constraints are the water/cement ratio (which should be replaced by a water/powder ratio), the cement content and the expected air volume which have to be considered in the total volume equation. With Figure 1 an example of this optimization tool is given. A standard SCC is compared with a mix designed following the introduced design method and the target curve, computed with the help of Eq. (2), is given as well. The good fit of optimized mix and target curve just as the deviation to the standard mix is obvious.

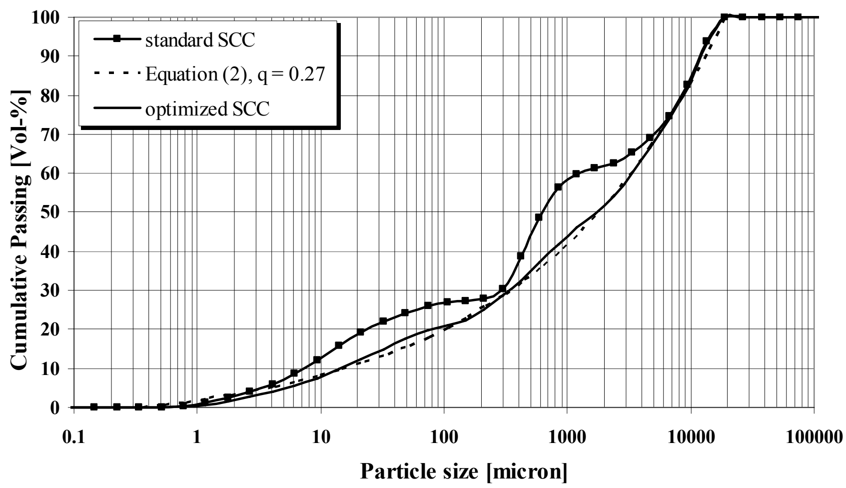


Fig. 1

Comparison of different SCC mixes regarding their PSD. The design parameters like $d_{max}$ and $d_{min}$ were kept constant

## Experiments

In preparation of production and testing of SCC in both fresh and hardened state various preliminary tests have been executed. As a basic design parameter the PSDs of all involved materials were determined. For aggregates this has been carried out by sieving whereas powder materials were characterized by means of Low Angle Laser Light Scattering (LALLS), better known as laser diffraction. Furthermore the water demand of the powder materials as well as of complete granular blends has been investigated extensively. The precisely determined water demand is considered to be one of the most important design parameters for SCC. Since the range of optimal workability for SCC is much narrower than that of Conventional Vibrated Concrete (CVC), even minor changes of the water content can lead to insufficient workability. For this purpose the common paste line tests according to Okamura /17/, the Vicat-test, the Puntke-test /18/ and the test according to Marquardt /16/ have been applied.

The latter test was used in a self-modified version and turned out to be a very reliable and quick test procedure. It is based on the monitoring of the mixing unit's power consumption while increasing the water content. As a result a test procedure was established, which allows the exact determination of the water content which represents the saturation percentage for this material. This characterizes the amount of water from which the granular blend can be compacted. The reproducibility of this test procedure is high and furthermore only one or two tests, respectively, are necessary to obtain a value for the water demand. All influences which affect the water demand like the particle shape, grading and specific surface area are considered doing this test. With the help of this procedure not only a reliable alternative for the determination of the water demand of powders is introduced, but also a simple possibility for quality inspection of incoming powder materials is given, since the change of the water demand is a good measure for changes in powder grading. Hence, time consuming and device related extensive PSD measurements can be replaced by the presented method. In Figure 2 an overview of water demands of different powders determined with the above-mentioned methods is given.

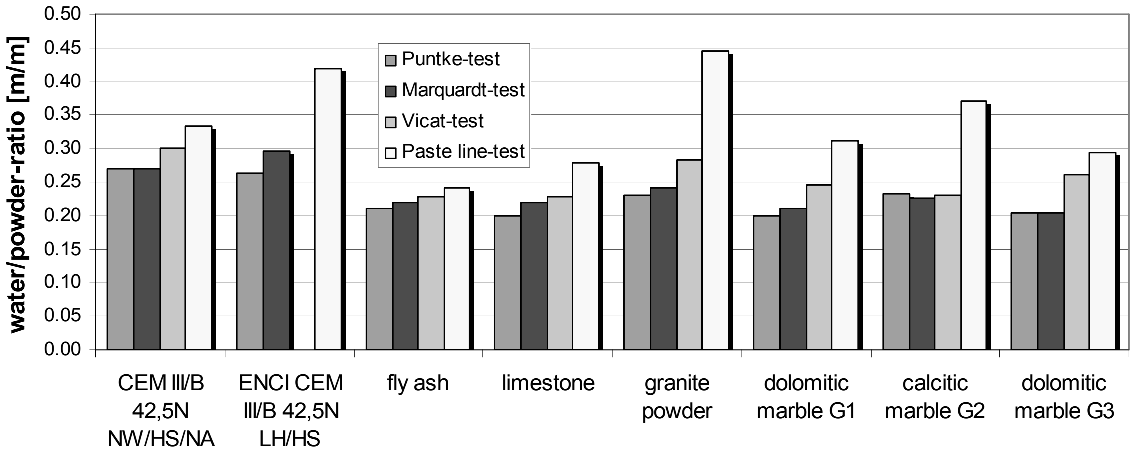


Fig. 2 Determination of water demands using different test methods

Subsequently, mortar experiments have been conducted in order to prepare the more time and material intensive concrete experiments. This is an indispensable step but during the test stage it also has been shown that results obtained with mortar tests cannot always be scaled up in a reliable way. For the evaluation of rheological properties of both mortar and concrete the tests, stated in Table 1 have been carried out largely following the recommendations given by /8/. Moreover, the fresh concrete density, the content of entrapped air and fresh concrete temperature have been monitored as well.

| Test method | Tested property | Measured |
|---|---|---|
| Slump-flow test | Flowability, relative yield point | Total spread |
| $t_{500}$ / $t_{600}$ time | Flow rate | Flow time |
| J-ring test | Passing ability | Step height and total flow |
| V-funnel test | Viscosity and filling ability | Efflux time |
| V-funnel ($t_{5\ min}$) | Resistance to segregation | Efflux time |
| Visual control of stability, sensitivity to bleeding and segregation, degassing ability and other observations | | |

Tab. 1

Overview about the tests for fresh SCC properties

For the evaluation of hardened concrete properties several mechanical and physical parameters have been determined. In detail these were the compressive strength and tensile splitting strength on cubes according to the corresponding European Standards and density as well as porosity parameters following the specifications given by the ASTM /2/. In continuation of the measurement of open porosity (porosity accessible to water) and total absorption of water, tests like capillary water absorption and penetration with water under pressure have been performed too.

**Results**

An integral objective of the above research was the investigation of the effect of grading (varying distribution modules) on different properties of concrete, in fresh as well as in hardened state. Another basic observation concerns the application of the water/cement ratio. Up to now the strength was given as a function of the water/cement ratio, the cement content and type of cement (it must be understood that there are also other influences). In applying the new design tool, unconventionally low cement contents (250 to 280 kg/m$^3$) were selected, the water/cement ratio therefore sometimes considerably exceeded the mark of 0.60. Considering the limits given for different exposition classes in the standards, this might be a handicap. Note that with these high water/cement ratios, no high total water contents are obtained. In evaluating the data gathered in the framework of these test series no distinct correlation between water/cement ratio and strength properties could be derived. Creating different states of packing with equal water/cement ratios, a broad margin of strength values was obtained and contrary equal strength was achieved with different water/cement ratios. Relating, however, strength to water/powder ratios (w/p) a clear linear correlation could be found. All particles smaller than 125 µm are counted as powder/fines. The data in Figure 3 show that for a certain amount of powder in a mix, the lowest possible water content should be found by means of grading optimization (with compliance of requested workability).

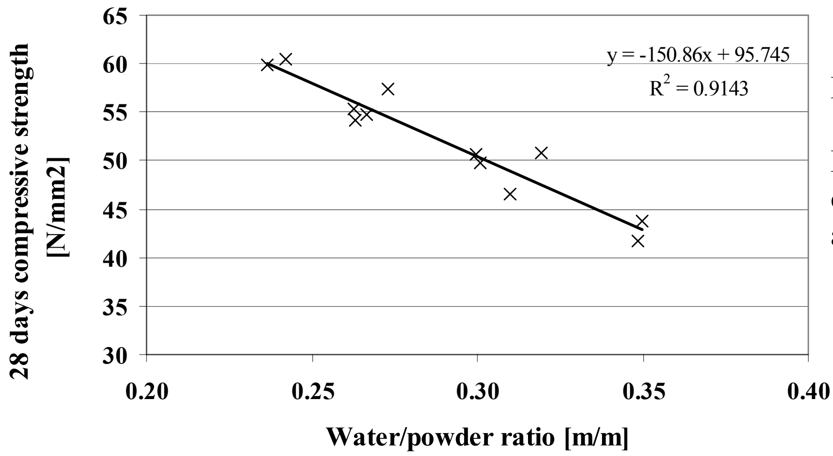


Fig. 3

Relation between the compressive strength and the w/p ratio

Focusing on the achieved compressive strength data, it can be noticed that the general level is high, knowing that a SCC was produced using a cement type CEM III/B 42,5N and aggregate sizes up to 32 mm (for most of the mixes). As filler material limestone powder, fly ash and stone waste powders (granite) were employed. The majority of strength measurements amounted to values in the range of 50 up to 60 N/mm$^2$ which is remarkable considering the fact that for most mixes only 270 kg of cement or even less was used.

In order to obtain evaluated data of the contribution of the cement content to the strength, the term cement efficiency should be introduced. This is defined as characteristic compressive strength ($N/mm^2$) per unit of cement content ($kg/m^3$). Based on an extended literature review with an analysis of given cement contents and obtained strength values it can be stated that for SCC the range of 0.10 – 0.14 is representative (e.g. /5/, /6/, /19/, /20/). It was found that for a significant number of examined historical cases the cement efficiency was even below 0.10. Here, following the introduced design method, values in the range of 0.20 – 0.22 could easily be achieved. Given that cement efficiency simply relates achieved strength to cement content, it is not the best evaluation tool yet, since the type of binder is not considered. Concerning this matter the introduction of a clinker-based measure, such as the *clinker efficiency* could also be a valuable parameter. In this way concretes produced from cements containing different clinker proportions can be compared. Note that for instance the presented SCCs have been produced with a blast furnace slag cement (CEM III/B 42,5N NW/HS/NA) containing only 24 % Portland cement clinker.

Besides the mechanical also the physical properties showed sound parameters. For the first instance, indirect measures for durability like the open porosity, the total water absorption and the capillary water absorption were tested. With the use of a 16-32 mm aggregate fraction higher porosity parameters were expected to occur. The negative impact of increasing aggregate size on the porous contact zone between aggregate and cement stone (Interfacial Transition Zone) is a generally accepted theory. However, the achieved measurements did not confirm this assumption. It was shown that improved packing achieved with the new mix design had a stronger effect. Comparing the capillary water absorption of different SCCs produced following the new mix design (Mix 1-3), obvious improvements compared to other, already optimized SCCs, containing 16 mm maximum aggregate size (Mixes A-C taken from /5/) can be noticed (cp. Figure 4). Furthermore the mixes 1-3 appear to obtain a steady-state condition after 28 days whereas mixes A-C still absorb water.

The open porosity accessible to water was found in the range of 7.1 up to 8.7 % (v/v) for the mixes containing 32 mm aggregates. For SCCs according to the new design concept containing 16 mm maximum aggregate sizes an open porosity of 6.8 % (v/v) was found. The corresponding total water absorption amounted to 2.9 %. This specific mix contained an unwashed granite sand 0-4 from a quarry in Scotland with a high amount of powders (11.5 %). Due to the application of this unwashed sand the amount of filler could be reduced as well. Other results obtained with this concrete support the application of unwashed sands (of constant quality) and stone waste powders.

Looking at the workability, a reduction of the water demand (related to the amount of powders) was found for decreasing values of q. A comparison of slump flow values and V-funnel times of fresh mixes having the same water/powder ratio indicates better workability for lower distribution modules. But mixes with higher amounts of powders and better packing, respectively also show higher cohesion forces which cause higher flow viscosities. With these facts in mind, another test series with mortars of varying grading and constant total water amount at different levels was carried out. Values for funnel time and slump flow showed for this case best workability for distribution modules around 0.35. Expanding from the mortar to the concrete scale, similar behaviour was found. SCC mixes with distribution modules smaller than 0.25 suffered from high relative viscosity which was expressed in higher funnel times (particularly stability time). Note that the relative yield expressed by the slump flow delivered sound values.

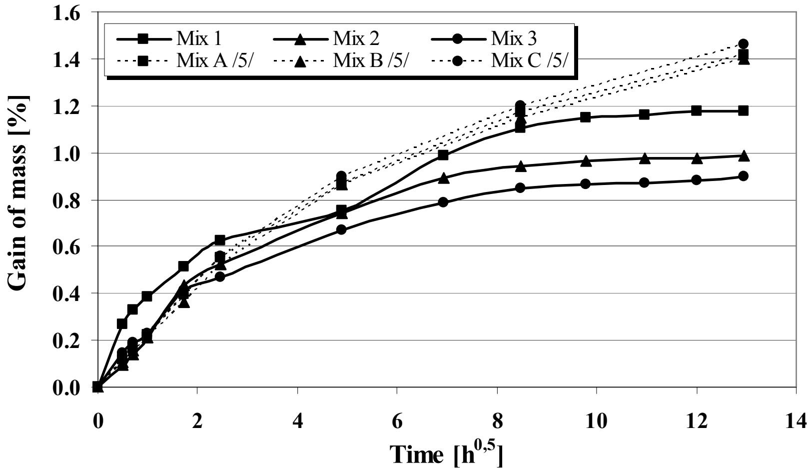


Fig. 4

Comparison of the capillary water absorption of mixes containing 16 mm max. aggregate size /5/ with mix 1-3 containing 32 mm aggregate sizes derived with the presented design method

## Concluding remarks

In this study a new design tool for SCC based on the controlled grading of the entire solid mix was introduced. It has been shown that grading has a fundamental effect on both fresh and hardened concrete properties. Here an improvement of various parameters was found for mixes with low cement contents and decreasing values of the distribution modulus q. Only viscosity was affected by too low q values. An optimum in regard to the workability was found for $0.30 < q < 0.35$. Furthermore the mechanical and porosity parameters were strongly enhanced by optimized packing. Dense packed granular blends showed good workability since less void fraction had to be filled with water and on the other hand also high strength values due to a dense packed granular skeleton. In this connection a raise of the compressive strength of more than 60 % in average based on the introduced *cement efficiency* was registered. Furthermore it was shown that broad grain size distributions with as many overlapping fractions as possible (within the bounds of practical possibility) and intermediate fractions (e.g. gravel 2-8) result in good packed mixes. The application of a broadly graded unwashed sand 0-4 (so including the fines) of broken granite also proved promising.

On the basis of sound indirect parameters of durability as well as on the compressive strength the minimum cement contents required by the standards seem to be a little outdated. The same applies for the water cement ratio for which it is recommended to replace it by a water/powder ratio. All these observations strongly suggest a change from the present prescriptive concrete mix design concept to a more performance-based design concept.

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