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The future of crushed sands?

Influence of the sand grain shape on the working properties of SCC mortars

Summary: In this paper, as the culmination of extensive tests, a method is presented which can be used to estimate the behaviour of crushed sands in SCC mortars in advance. The algorithm described provides an initial basis for an empirical model that enables the derivation of information on the working properties of SCC mortars from only the results of analysis of the grain shape and grain size distribution of the starting sands. The key parameters are the Fuller exponent n of the grain size distribution and the shape parameters sphericity and roughness.

1 Introduction

Crushed sands are usually a by-product of the production of ballast and chippings, accounting for up to 20 % of the yield. With simple comminution methods, crushed sands with a fine grain content of 15-25 mass % are produced "by the way". They are only used in high-grade applications providing the entire comminution and processing flow undergoes cost-intensive optimization. Depending on the regionally dependent availability of extracted materials, however, they are currently either just dumped or used for inferior backfilling, as cable sands or in frost protection courses.

The increasing use and further development of self-compacting concretes (SCC), as well as growing awareness of the construction industry of the economic and ecological use of existing environmental resources have opened up a new range of application for crushed sands. The specific properties of self-compacting concrete, such high flowability and independent deaeration, are realized with a high content of filler components with a grain size < 125 µm and the use of plasticizer. Currently mainly fly ash and silica dust with a grain shape as round as possible are used as filler and natural sands are used as fine aggregate. In addition, the packing density, which is primarily influenced by the grain size distribution of the bulk solid, but also by the particle shape of the individual grains, was frequently used as sole characteristic for the summary description of all granulometric characteristics. With the development of new measurement methods for determining the grain shape and grain size, these relationships can be quantitatively analysed both for coarse and fine aggregates.

Dumps of crushed sands at a quarry

2 Granulometric characteristics

The grain shape and grain size of 60 different sands were analysed with the HAVER CPA 4-2 real time photooptical particle analysis system (referred to as CPA in the following) supplied by HAVER & BOECKER [1], which is installed at the Department of Building Materials Processing and Recycling (ABW). According to the principle of dynamic image analysis, the system analyses particles as they free-fall past the measurement plane with a line camera in backlight mode and internally breaks down the measured data into 255 size classes. The following grain shape parameters are important for the further explanations:

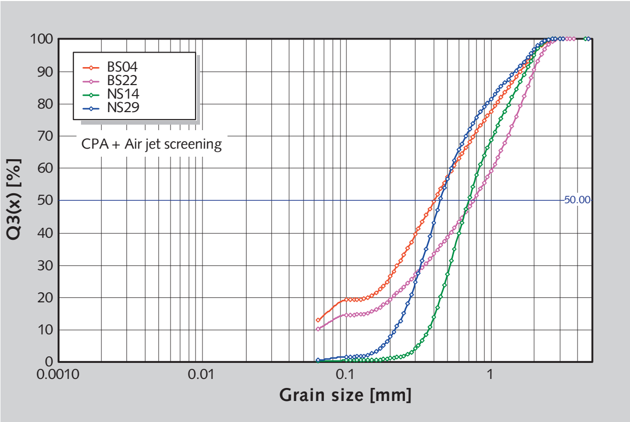
Sphericity according to ISO 9276-6.2: $SPHT = \frac{4 \cdot \pi \cdot A}{P^2}$ [-]

Roughness: $R = \frac{\text{mean circ}}{\text{mean } {}^{L}/_{W}}$ [-]

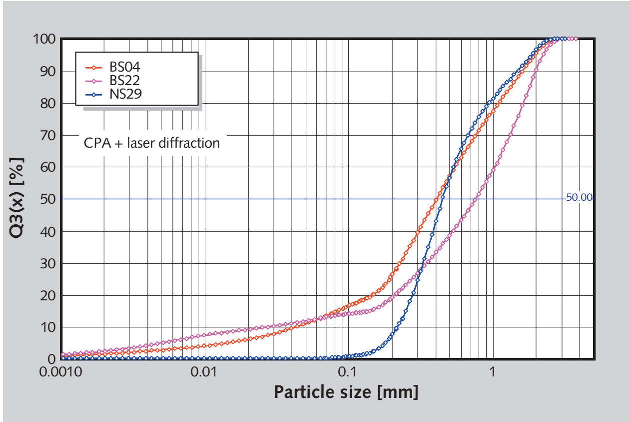
The surface properties were described based on the system-internal definition of the CPA using the roughness parameter. This is calculated for each particle size class with the quotient of the mean circularities (circ = $P/2 \cdot [\pi \cdot A]^{0.5}$) and the mean L/W ratios. With this model, the roughness is expressed as a function of two parameters – the surface roughness and the grain shape. The ideal condition is defined based on a "smooth ball" and has the value R = 1. Real aggregates achieve values < 1.

The grain shape of the sands could be imaged in good quality up to a grain size of 400 µm and approximated up to around 100 µm. The grain size could be measured up to a size of 100 µm with the CPA system. Characterization of the size range < 100 µm was limited in previous research to separation of the sand samples at 100 µm and a single measurement at 63 µm by means of air jet sieving. For materials with up to 25 % fines, however, such a characterization is not representative for a grain size distribution. Therefore in further studies, for the fines, laser diffraction analysis with the Coulter LS 230 particle sizer supplied by Beckman-Coulter (referred to as Coulter in the following) was used.

This sizer operates with two measurement cells through which the sample flows consecutively. This enables a combination of two measurement principles – laser diffraction in the Fraunhofer range and light scattering in the Mie range (grain sizes around < 0.4 µm), and a measuring range from 0.040 µm to 2000 µm in 116 size classes. Deionized water with electrolyte addition was used as measurement fluid. Dispersion was performed with ultrasound. In previous labo-



1 Grain size distribution with combination of the results of the CPA and air jet screening



2 Grain size distribution with combination of the results of the CPA and the Coulter

ratory tests, comparison of results of the CPA and the Coulter analyses resulted in good agreement of the measured grain size distributions even for non-spherical grains. For the evaluation of the grain size distribution of the entire grain size range, the measuring results of the CPA (> 100 µm) and the Coulter (< 100 µm) were combined with an overlap of ± 25 µm using the PMPcompact software supplied by Grainsoft. Particularly for the grain size distribution of the crushed sands with high fine content, this procedure returned new results. In **Fig. 1** and **Fig. 2**, the grain size distributions from the CPA analysis and air jet sieving and those from the CPA and Coulter analyses are shown based on selected natural and crushed aggregates.

The grain size distribution is described with Fuller's distribution function:

Fuller distribution: $$Q_3(x) = \left(\frac{x}{x_{max}}\right)^n \quad [-]$$

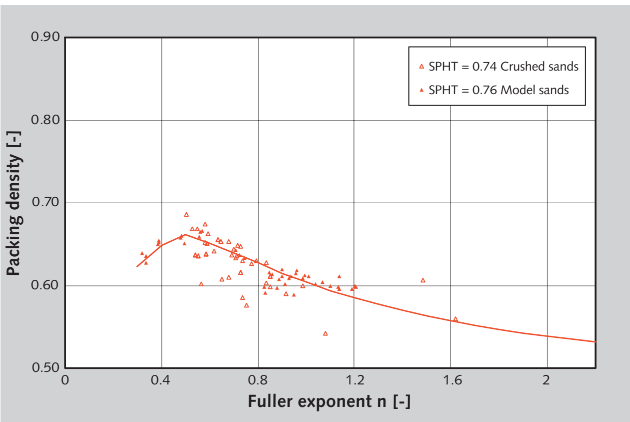
The exponent n characterizes the width of the distribution. With increasing n (natural sands), the distribution becomes narrower, i.e. the undersize curve becomes steeper. Crushed sands have a wide grain size distribution and therefore a low Fuller exponent. Working on the extension of the particle size distribution by means of Coulter analysis, calculation of the Fuller exponent could be extended to the entire grain size range to a grain size of 0.04 µm. The comparison of the evaluation of the grain size distribution after Fuller shows a considerable change in the n-values.

The packing density PD characterizes the relative space filling of a bulk solid and is calculated as follows:

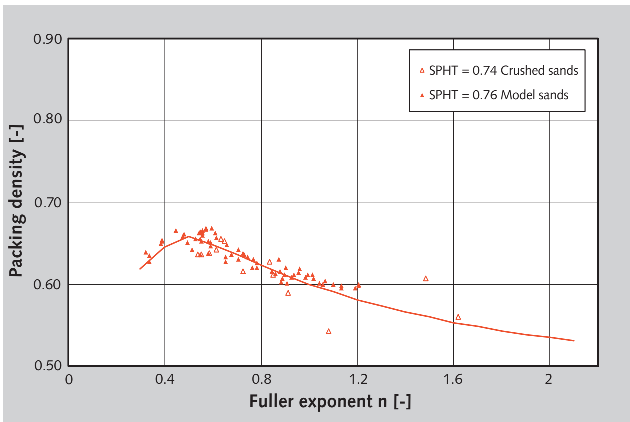
Packing density: $$PD = \frac{\rho_{tap}}{\rho_{particle}} \quad [-]$$

For determination of the tap density, the sands were compacted for 60 s by means of vertical vibration without applied load. The advantages of the combination of photooptical image analysis and laser diffraction analysis and therefore of the representative characterization of the grain size distribution are shown clearly in **Fig. 3** and in **Fig. 4** especially for crushed sands. On plotting of the packing density as a function of the Fuller exponent, which was determined for the entire particle size range from 0.04 µm to the maximum particle size x_{max}, the measured points are subject to far smaller variations than before and fit very well with the trend.

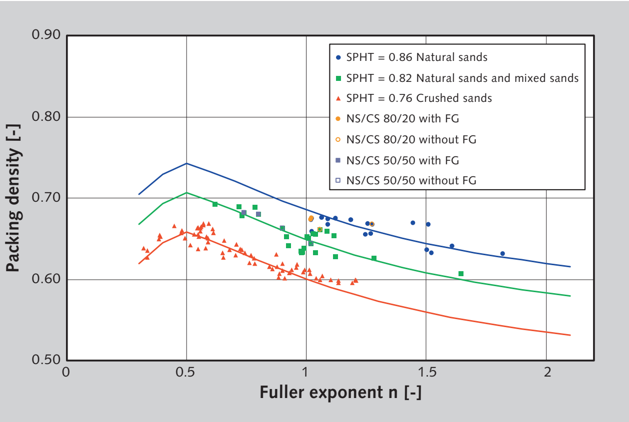
The plotted curves were calculated with the equation of Peronius and Sweeting [2], which is based on Fuller's results



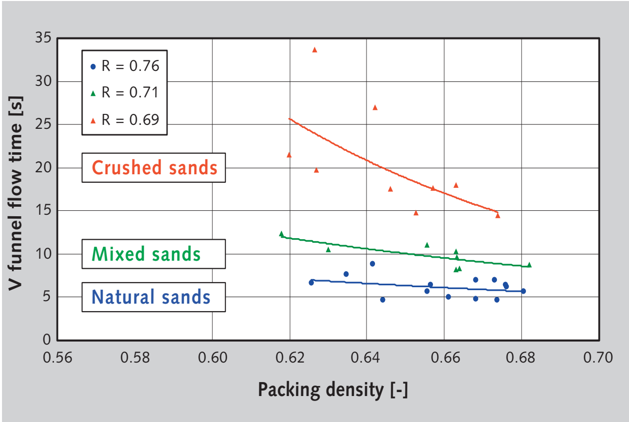
3 Relationship between packing density and Fuller exponent n – corresponds to Fig. 1



4 Relationship between packing density and Fuller exponent n – measured with CPA and laser diffraction



5 Measured values for natural and crushed sands in comparison with the curves calculated after Peronius and Sweeting



6 Relationship between the packing density and V funnel flow time at the same slump

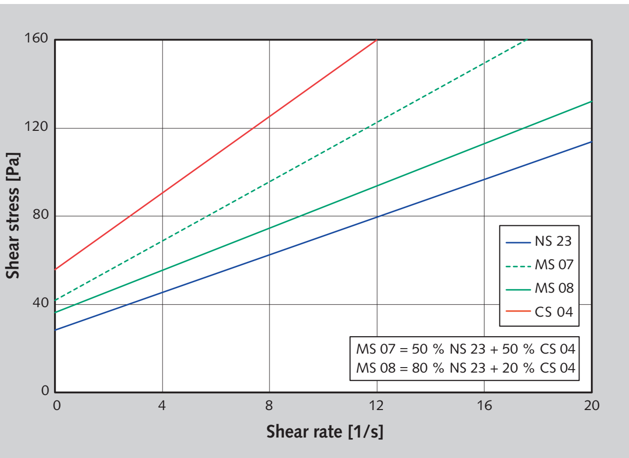
with Powers' shape factors. The packing densities of all natural and crushed sands as well as of blends of natural and crushed sands are shown in the following diagram. These curves correlate well with the measured results. On the one hand, the packing density increases independently of the grain shape with falling distribution exponent to a maximum value at an n of around 0.5. On the other hand, it rises with the roundness of the particles, i.e. with increasing sphericity. For the sands analysed, this means that high packing densities are achieved for sands with narrow grain size distributions and well-rounded grain shapes (high SPHT) as well as for sands with low Fuller exponent n and low SPHT values.

Depending on the blend composition, the values for the sand blends can be assigned to the corresponding curves after Peronius and Sweeting (**Fig. 5**). At the mixing ratio of 50 % NS and 50 % CS, they fit well with the middle curve, which is used for natural sands with a relatively low sphericity (0.82). At the mixing ratio of 80 % NS and 20 % CS, they lie in the range of values measured for the sphericity of 0.86, that is the well-rounded natural sands. The shift of the measured values towards lower sphericity values is plausible because the sphericity of the blend decreases with the increasing content of crushed sand.

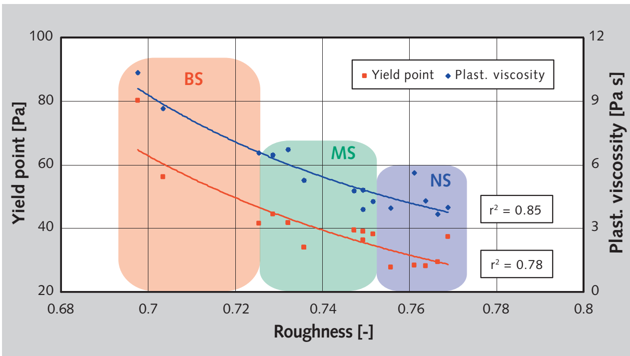
In comparison with the mixing ratio, the content of natural fine grain (FG) in the 80/20 % blends is of minor importance. With reference to the example of the 50/50 % blend, it is clear that the samples with fine grain achieve a wider grain size distribution and, as expected, higher packing densities than the 50/50 blends from which the fine grain content of the crushed sand has been sieved off and removed.

3 Influence of the granulometric characteristics on the working properties of SCC mortars

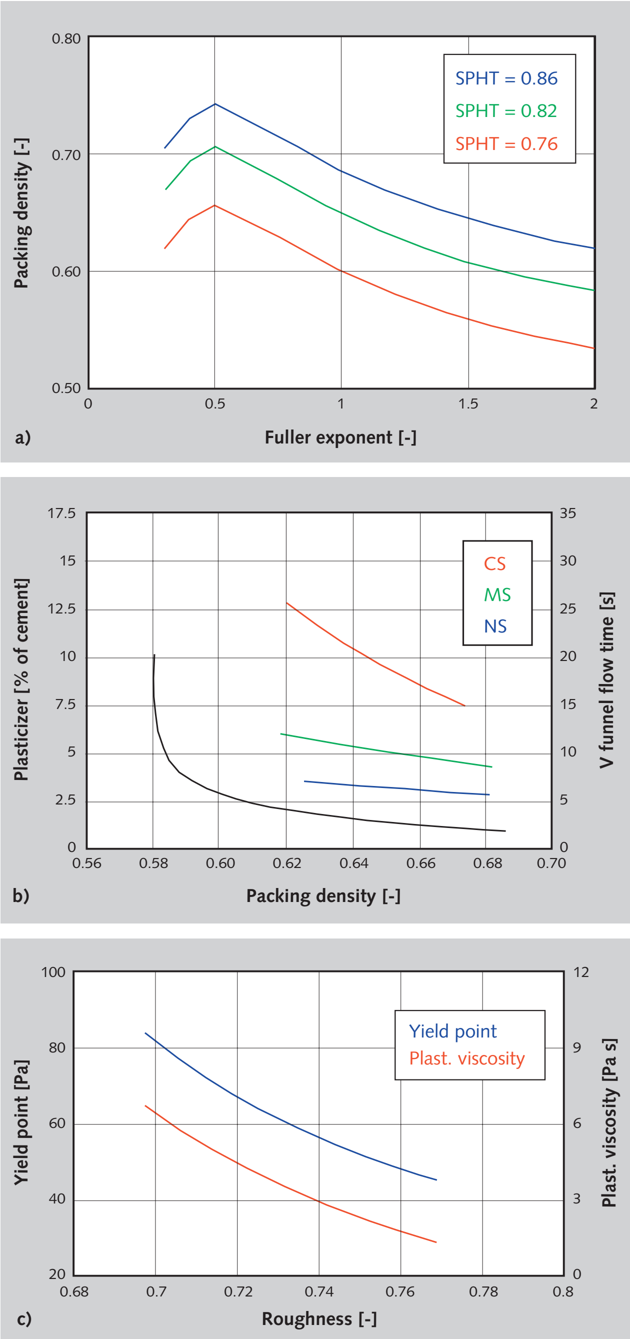
To establish comparability in respect of the effect of the crushed sands in the mortar, for all mortar tests a base formulation was defined. The blend contains a constant quantity of cement (CEM I 52,5 R), sand (size 0.125/2) and water (w/z = 0.6). The amount of the fine grain content, which consists of fly ash and the fine grain content of the respective sand, is also kept constant. For description of the working properties, the single-point measurement methods slump and V-funnel flow time as well as the rheological parameters determined with a rheometer were used. The procedure was such that first the flowability of the mortar was adjusted to a defined slump of 24.5 ± 1 cm with the addition of a plasticizer. For all mortars, polycarboxylate ether was used as the plasticizer.



7 Bingham approximation of typical sands with different grain shape



8 Influence of the roughness on the rheological parameters yield point and plastic viscosity



9 a, b and c Estimation of the working properties for a formulation with w/z = 0.6

On the basis of the required amount of plasticizer, a comparison of the sands used is possible. With decreasing packing density of the sands used, the amount of plasticizer increases exponentially until flow is no longer possible (cf. Fig. 9 b). With the amount of plasticizer determined, mortar blends were then prepared for determination of the V-funnel flow time as well as for the rheological measurements with the Viskomat NT supplied by Schleibinger with the measurement insert after Prof. Vogel [3]. In Fig. 6, the results of the single-point measurements show the influence of the packing density on the V-funnel flow time at the same slump. Significant here is the differentiation of the measured values in three groups of curves, as a function of the roughness of the grains. The rougher the grains are, i.e. the lower their R value is, the longer the V-funnel flow time is. Further, it should be noted that with greater roughness of the grains, the packing density has a greater influence on the flowability than with grains with a smoother grain surface.

Fig. 6 also shows that, on the basis of the guide value of 10 s for the V-funnel flow time recommended by Okamura [4], the use of crushed sands alone cannot be considered for practical use, whereas partial substitution of natural sands with crushed sands is certainly possible (green curve). In the course of the rheological measurements with the Viskomat NT, it was established that owing to the measurement range of the rheometer, only mortars with a V funnel flow time up 15 s could be measured. The flow behaviour of the analysed mortars can be characterized with the Bingham flow model $\tau = \tau_0 + \eta_{pl} \cdot \dot{\gamma}$. The yield point τ_0 and the plastic viscosity η_{pl} are the rheological constants of this equation. Depending on the type of sand, the averaged flow curve consists of at least three single measurements (for crushed sands, several measurements were necessary). Fig. 7 shows representative examples of this. The figure clearly shows that, depending on the sand used, the mortars exhibit different rheological parameters. That means mortars prepared with crushed sands achieve much higher values for the plastic viscosity and the yield point than mortars prepared with natural sands.

In the evaluation of the measured granulometric values, it became clear that the roughness is a key factor for influencing the rheological properties (Fig. 8). The correlations of the rheological parameters with the other granulometric characteristics sphericity and Fuller exponent are much lower so that an assignment to the sand types is only possible based on roughness. The roughness characteristic implies both the geometric dimensions of the grains as well as their sphericity.

4 Development of an empirical model

On the basis of the measured results for the grain shape and for the surface properties as well as the grain size distribution of the starting sands, in line with Fig. 9, it is possible to estimate the working properties of the SCC mortars to be produced in three steps. Necessary for this are only the granulometric parameters Fuller exponent n, calculated from the grain size distribution, as well as the particle shape sphericity and roughness. In the first step, using the Fuller exponent n and the sphericity from Fig. 9 a, the expected packing density can be derived. If the value determined for the packing density is lower than around 0.6, the required amounts of plasticizer and the V-funnel flow times increase steeply until the defined slump is reached. As the sands here are mainly crushed sands, these should only be used in blends with natural sands.

If the packing density is higher than 0.6, in the second step, the necessary amount of plasticizer is determined from Fig. 9 b. The values for the V-funnel flow times in Fig. 9 b already permit assessment for the practical use of the blend. Flow times > 11 s are unacceptable. In the last step, in Fig. 9 c on the basis of the roughness of the starting sand, the rheological parameters yield point and plastic viscosity can be estimated. If in step 2, with mixing of the crushed with natural rounded aggregate, a modification of the starting sand is achieved, this improvement in the quality also has an effect on the roughness of the overall blend and therefore the flow properties.

The algorithm described provides an initial basis for an empirical model that can be used to obtain information on the working properties of mortars from only the results of the analysis of grain shape and grain size distribution for the formulation analysed. On this basis, a method was developed for determination of the quality and quantity of crushed sands for use in SCC mortars prior to actual mortar production.

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