Natural Stone Waste Powders Applied to SCC Mix Design

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Abstract

In order to comply with current trends concerning sustainability, saving of primary materials and energy savings, this paper addresses Eco-concrete. The major focus thereby is on the increased efficiency of cement use. Applying a new mix design method for concrete, cement contents can be decreased and partially be substituted by other fine powders, preferentially by waste powders which have no mass application so far. This paper is giving examples of successfully introduced waste powders and characterizes the concretes produced with these powders. These innovative, low cement concrete types obtain medium strength and exhibit furthermore self-compacting abilities. This paper additionally highlights possibilities for the direct use of natural stone sludges or filter cakes. A new grading based design method, developed in the authors' research group, enables the efficient use of all materials available. The method is applicable to self-compacting concretes, earth-moist concretes and conventionally vibrated concretes.

Keywords: rock waste powder, SCC, cement content, concrete mix design

Mehlkornfeine Abfallstoffe der Natursteinindustrie in der Projektierung von SVB

Zusammenfassung

Um den derzeitigen Bestrebungen nach Nachhaltigkeit und Material- beziehungsweise Energieeinsparung Rechnung zu tragen, ist dieser Beitrag dem Thema Öko-Beton gewidmet. Dabei liegt der Schwerpunkt auf einer effizienteren Nutzung von Zement. Durch die Anwendung eines neuentwickelten Betonentwurfskonzeptes kann der Zementgehalt verringert und teilweise durch andere Feinstoffe, bevorzugt Gesteinsabfallmehle, ersetzt werden. Der vorliegende Artikel zeigt Beispiele von erfolgreich eingesetzten Gesteinsmehlen auf und beschreibt die damit produzierten Betone. Diese Betone mit geringen Zementgehalten erreichen mittlere Festigkeiten und zeigen darüber hinaus selbstverdichtende Eigenschaften. Weiterhin wird auf die Möglichkeit der direkten Nutzung von Filterkuchen oder Gesteinsschlämmen aus der Natursteinindustrie eingegangen. Mit Hilfe eines neuentwickelten, auf Korngrößenverteilungen basierenden Betonentwurfs, können diese Abfallstoffe wirksam für die Herstellung von erdfeuchten oder selbstverdichtenden Mischungen sowie für Standard-Rüttelbetone genutzt werden.

Stichwörter: Gesteinsmehle, SVB, Zementgehalt, Betonentwurf

1 Introduction

Concrete is, compared to other construction materials one of the most sustainable materials when assessing following the concept of embodied energy [1]. However since almost 15 billion tons of currently produced concrete p.a. generate the largest material flow on earth, in absolute terms concrete production represents the biggest overall impact on the environment within the construction industry. It is said, that concrete production could soon be responsible for about 10 % of the total greenhouse gas emission [2]. Within concrete the cement content has the most significant impact on the environment. More than 2 billion tons of cement were produced last year. This cement created CO_2 in two ways during its production. First, during the conversion of calcium carbonate to calcium oxide, CO_2 is formed process-related inside the kilns and secondly, quantities of fossil fuels needed to heat the kilns above 1,450 °C release CO_2 to the atmosphere [2]. For the sake of completeness it should be noted that caused by the carbonation process a minor percentage of CO_2 is later taken up by the concrete.

With the ratification of the Kyoto treaty in February 16th, 2005 and also due to steadily rising oil prices there is an additional stimulation to improve energy management of cement and concrete industry and therewith sustainability of the material cement. However, a more efficient use of cement could improve this situation greatly as much cement actually acts as filler, which could be better done by inert materials. Besides this, in cement as such, clinker could be replaced by supplementary cementing materials (SCM), such as slag and fly ash. This study addresses the replacement of Portland cement (OPC) by rock waste powder.

2 Rock Waste Powders

Rock waste origin

In all quarry operations fines are collected during the whole process chain by particle filter devices. Those fines are in dry state what eases their application in concrete mixes, but their amount is relatively small in comparison to fines produced during the washing process of broken aggregates. Depending on the type of rock and the applied crushing units this can vary notably. Fines are removed from the material to be washed by wet sieving and/or separation in hydrocyclones. The outcome of this process is a slurry highly loaded with a fine fraction of the appropriate rock type. This slurry is sometimes pumped directly into settling ponds where it represents an environmental burden on the water and soil. For a better handling afterwards those slurries are often treated be means of a filter press. In that way, water will be removed from the material to a great extent. Depending on the applied pressure during pressing, the pressing time itself and the grading of the fine fraction, the remaining filter cake contains an amount of water from 18 up to 30 % (m/m). In this solid state the material can be easier transported by wheel loaders or band-conveyors and piled afterwards.

Fines are also generated in the ornamental stone industry. During drilling, grinding, polishing, and first of all sawing large volumes of fines are produced. Calmon et al. [3] specifies for the Brazilian situation, the volume fraction of a marble stone block which results in 30 % sawing waste producing slabs of 1-3 cm thickness. Laskaridis gives similar figures for a Greek company [4]. Prevention of landfill and a useful application of these rock powders would therefore constitute a great environmental benefit.

Rock waste characterization

In the following two rock waste materials are introduced. These are on the one hand granite and on the other hand a dolomitic marble material. The granite is originated during the washing of crushed granite rock for the aggregate production whereas the marble comes from the ornamental stone industry. Both wastes are generated as slurries and are subsequently treated by filter presses. The water content of the resulting filter cakes has been determined by drying in an oven and is given in Table 1. For the granite material the determination was repeated several times and therefore a range can be given. The determination of the specific particle density for both materials was carried out according to EN 1097-7 by means of the pycnometer method. Besides Blaine measurement for the marble material, specific surface area calculations have been carried out for both materials based on the particle size measurement (cp. Figure 1) and their shape factors [5]. This data can be taken from Table 1 as well. Water demands, necessary for concrete design have been determined by means of the spread flow test. The notably higher water demand of the granite powder can be explained by the rougher surface and the more angular and flaky

Table 1: Physical properties of the applied stone waste materials

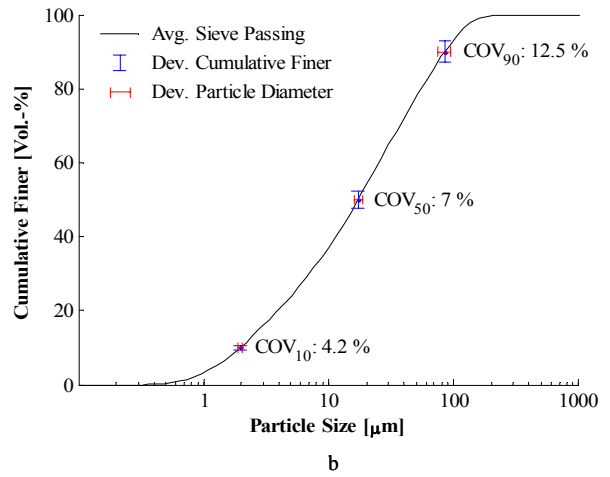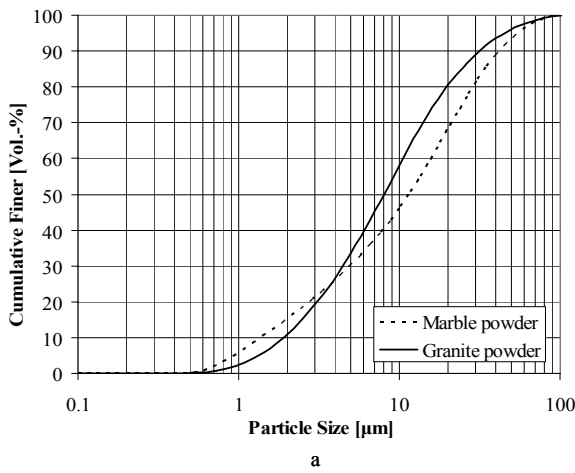| Property	Granite	Marble
Water content of the filter cake [%, m/m]	18.8 - 23.7	20.9
Specific density [g/cm^3]	2.724	2.801
Blaine specific surface [cm^2/g]	-	4580
Computed specific surface area [cm^2/cm^3]	13,051	14,739
Shape factor [-]	1.36	1.25
Computed specific surface area, corrected for shape [cm^2/cm^3]	17,734	18,426
Water demand β_p	1.215	0.874

Figure 1: Particle size distribution of the marble and granite fines (a), variance in the granite PSD of the granite fines in the framework of a monthly quality check over a period of 10 month (b)
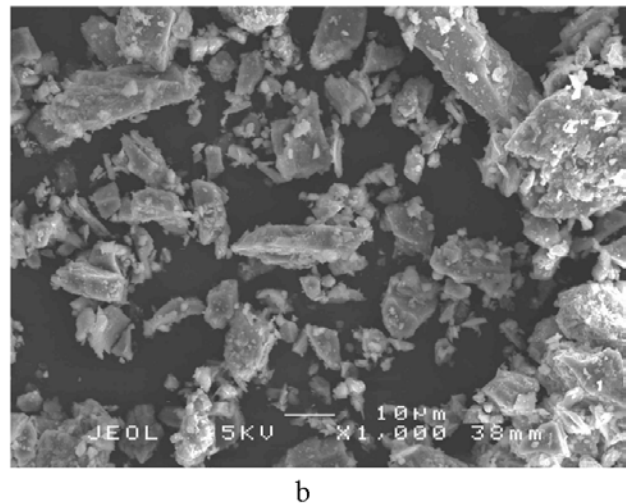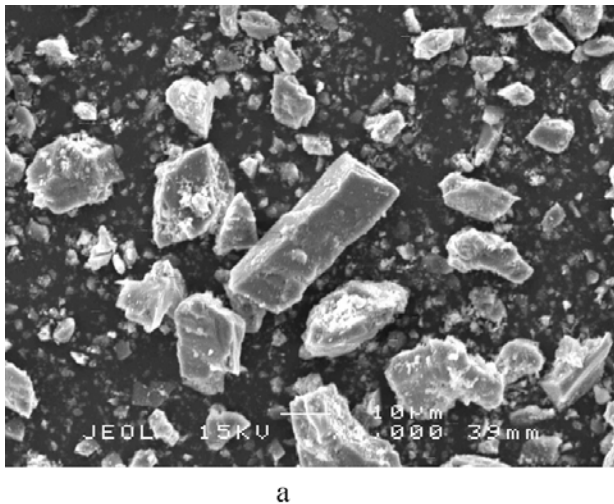

Figure 2: Morphology of the marble (a) and granite (b) powder (1,000-times magnified)

shape compared to the marble particles. This becomes obvious comparing the morphology of the particles using SEM examinations (cp. Figure 2).

The particle size distribution (PSD) measurement was executed by means of a Malvern Mastersizer 2000 laser diffractometer in liquid dispersion. From Figure 1 (a) it can be seen that both materials are comparable in size range. This is also confirmed by a similar specific surface area. Furthermore, the homogeneity of production was tested for the granite material in the framework of a monthly PSD measurement. The results are given in Figure 1 (b). It turned out that the variation in particle size distribution is only small and therefore the material is in this respect suitable for concrete production. It should also be noted that the granite material is not expected to cause Alkali Silica Reaction (ASR). Appropriate tests for ASR susceptibility have been executed.

3 Mix Design Theory with Respect to SCC

Self-Compacting Concrete or sometimes also referred to as Self-Leveling Concrete was first developed in 1988 in Japan [6]. Motivated by a lack of skilled workers and a substantial number of durability damages due to insufficient compaction, Okamura announced in 1986 the necessity to employ a self-compacting concrete, which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction.

In opposition to the common standard literature on SCC Nagataki [7] assigns SCC to the superplasticized, anti-washout, underwater concrete mixtures, as a further development of them. These anti-washout, underwater concretes were first developed during the 1970s in Germany. Both concrete types, underwater concrete and SCC, have a high segregation resistance and high fluidity in common.

The mix design method developed by Okamura and Ozawa, henceforth called the Japanese mix design, is still the base for most of the SCC production. Despite the great improvements added to concrete industry this design method is, however, related to a number of restrictions. There is for example, the coarse aggregate content limited to 50 % of the solid volume in order to prevent blockage of aggregate particles [6]. Moreover, the sand fraction is fixed to 40 % of the mortar volume. In order to obtain sufficient viscosity, high amounts of powder have been added,

which was for the most part realized by cement. Therefore, many SCC designs show elevated cement contents, which led to the situation that cement was "wasted" as filler. High amounts of cement can cause thermal cracking or strength in excess, which can demand for additional reinforcement.

In 2003 a new method for the design of flowing concrete was introduced by Su and Miao [8]. This Chinese mix design considers the state of packing of all aggregate fractions integrally. Therefore, a packing factor is introduced, which governs the amounts of sand and gravel. In a next step the remaining voids in the granular skeleton are filled with paste, similar to the Japanese mix design concept. Nevertheless, having a closer look on the logarithmic scale of these aggregate particle sizes, it appears that only three decades, from 100 μm to 100 mm are involved in such optimization (cp. Figure 3). However, considering all solids including the powder fraction, at least three more decades exist in the solids range (down to 100 nm), which represent by far the biggest specific surface area within the mix, the highest contribution to mix costs, and also a notable volume share.

Brouwers and Radix applied and modified the Chinese mix design concept [9]. One of their major conclusions was that the particle size distribution (PSD) of all solids in their good performing mixes have similarity to the modified grading lines from Andreasen and Andersen [10].

The common Fuller curves as well as the original Andreasen and Andersen model prescribe a grading down to a particle diameter of zero. In practice, however, there will be a minimum particle size, given by the finest powder involved. Accordingly, a modified version of the Andreasen and Andersen model was applied that accounts for the minimum particle size in the mix [11]. This modified PSD (cumulative finer fraction) reads:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \qquad (1)$$

with D_{min} and D_{max} being the minimum and maximum particle diameter and q being the variable distribution modulus (q = 0.5 in the Fuller curve).

Based on this grading curve and the observations above, a new mix design model is developed, now considering the entire size range. This design tool generates continuous grading for all solids resulting in improved workability and stability as well as
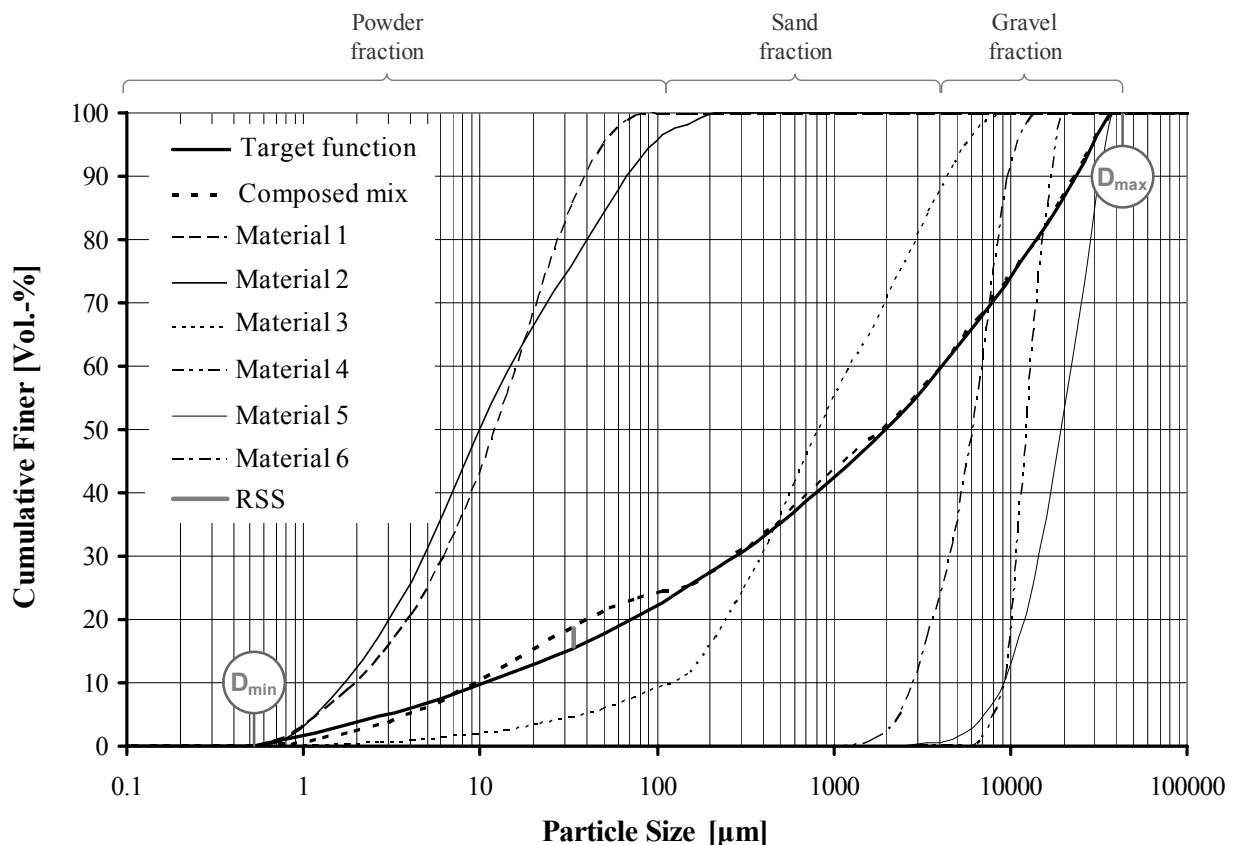
Figure 3: Background of the new design method showing the target distribution (bold line), the obtained composed mix (dotted line) and the individual starting materials (materials 1-6).

improved hardened properties due to denser packing of particles. The basis for the design tool is the thorough analysis of the individual materials in regard to their PSD. Furthermore, the modified Andreasen and Andersen curve serves as a target function for the subsequent granular optimization of the individual materials. Minimum and maximum particle sizes are thereby given by the applied materials and a distribution modulus has to be chosen depending on the desired mix characteristic; $0.20 < q < 0.50$ appears to be a suitable range for common concrete applications. With the help of an optimization algorithm the percentages of the individual materials are varied until a best possible fit of the composed mix with the target function is achieved. Thereby the target value, which needs to be minimized by means of the Least Squares Method (LSM), is the deviation between target curve and composed mix, expressed by the sum of the squares of the residuals (RSS) at defined particle sizes. In Figure 3 this situation is explained. In order to assess the quality of the optimization a coefficient of determination R^2 is computed for comparative purpose [12]. The assessment of the RSS is conducted

at all particle sizes known from the PSD analysis (by means of laser diffraction in the powder range and sieving for the sand and gravel fraction).

As geometric random packing is modeled, the optimization proceeds with a fixed increment, being the ratio of two subsequent particle sizes D_{i+1}/D_i. Here the step size is close to $\sqrt{2}$ for the powders characterized by laser granulometry, and $\sqrt{2}$ for the materials characterized by sieving. Note that for the standard sieve set this factor amounts to 2. With these narrow steps the optimization is assumed to be precise and the assessment is equally distributed over the complete size range so that all fractions are equally weighted.

Moreover, the algorithm accounts for some constraints, which come from the practical needs of the concrete industry. First, the model is based on the volumetric composition of one cubic meter fresh concrete containing an arbitrary volume of entrapped air. Secondly, minimum and maximum cement amounts (or fixed cement amounts) can be put into the model in order to satisfy the needs of exposure classes like given in EN 206-1. Further-

more, the water content can be varied by giving water/cement ratios or water/powder ratios into the optimization algorithm. All particles smaller than 125 micron are considered to be powder, whether they are reactive or not.

Applying this new design concept generates highly workable mixes with improved packing. A notable increase in strength was observed compared to conventionally designed concretes, which led to a reduction of cement amounts (a more efficient use of cement) and an increase of supplementary cementing materials (SCM), like for example stone waste powders.

4   Experimental Program

In the following two different SCCs are exemplarily presented which have been designed applying the introduced concept. Theses mixes represent a selection of a variety of successfully designed mixes. Moreover, these mixes show low cement contents and high volumes of stone waste powders.

The execution of mortar tests is, especially for the needs of SCC of importance in order to adjust water and admixture dosages to achieve desired workability. The common spread flow test, known from SCC production is recommended for determining the water demand of a mix. However, experience has shown that a computed overall β_p, based on the individual materials and their mix proportions is not suitable, especially when designing dense packing. Due to improved packing and enlargement of the particle size range in both fine and coarse direction, the water demand of a granular mix will be lower than the sum of water demands of its individual ingredients. This is in contrast to Domone and Wen, who conclude to predict with reasonable confidence the water demand for pastes containing mixtures of powders [13].

Mix compositions
The results of the mortar tests, after adjusting the admixture and water contents, are not separately shown since the achieved properties correlate well with the full scaled concrete tests. Mix A was designed in order to comply with exposure class XF1, which represents a common case. Therefore the cement content was chosen to be 300 kg/m^3 and the w/c ratio was set to 0.55. A stone waste component is introduced by using unwashed granite sand 0-4, which contains about 11 % of powder (cp. Figure 1). During the washing process of aggregates energy and large amounts of water are

required. This test shows that unwashed sand originating from crushed rocks can be applied as well. The mix proportions are given in Table 2. Moreover, Mix A also contains a notable amount of gravel 16-32. This coarse fraction is not typical for SCCs since it can easily cause blocking. On the other hand, this coarser fraction improves the packing density.

Mix B represents a more performance based concrete type as the applied cement amount of 200 kg/m^3 is far below required minimum contents. Note that the exposition class with lowest requirements (XC1) already demands 280 kg/m^3 for reinforced structural elements. Furthermore, Mix B contains notable amounts of marble waste slurry. The slurry was dried before and roughly crushed, but not repulverized as in the case of [3]. In previous research it has been shown that the slurry can be directly added to the mix if stable concentration is assured. Neither SCCs contain an auxiliary admixture such as a viscosity modifying agent.

Concrete properties
Mix A shows good fluidity represented by a slump flow of 730 mm in fresh state. The moderate relative viscosity, expressed by the V-funnel time seems to be caused by the fine and angular granite particles. In general the granite fines have been identified to slightly increase viscosity compared to other natural stone waste powders. However, also the coarse 16-32 mm gravel fraction contributes to the viscosity increase. This fraction is also responsible for the V-funnel stability time of 2.2 seconds, which is still in the limits of the suggested maximal 3 seconds [14]. Recapitulating it can be said that Mix A fulfills all requirements for SCC. The relevant fresh concrete properties are summarized in Table 3, based on the tests described by [9] and [14].

Mix B possesses a notably lower yield stress by also using less superplasticizer compared to Mix A. Besides high fluidity this mix also shows low relative viscosity expressed by very short funnel times and t_{50}-times. Despite the low viscosity the mix stays stable (almost no measurable stability time) and is not prone to blocking (J-ring step).

Concerning the properties in hardened state the strength development is taken as a common characteristic to assess the potential of the introduced design method, particularly with regard to the low cement contents applied. As an OPC was applied the increase in strength between the 7th and 28th day is no longer high (cp. Figure 4).

Table 2: Composition of the SCC mixes

Material	Mix A		Mix B	
	dm^3/m^3	kg/m^3	dm^3/m^3	kg/m^3
Cement CEM I 52.5 N	97.9	300.0	65.3	200.0
Limestone powder	68.8	184.3	-	-
Marble powder	-	-	140.7	394.1
Sand 0-1 (fine river sand)	-	-	59.2	156.0
Unwashed granite sand 0-4	342.5	907.1	-	-
Sand 0-4 (river sand)	-	-	253.4	669.6
Gravel 2-8	67.8	179.6	152.5	399.5
Gravel 4-16	12.3	32.0	125.9	328.0
Gravel 16-32	220.3	583.9	-	-
Water	165.0	165.0	191.0	191.0
Admixture (Glenium 51)	3.2	3.5	2.5	2.74
Air	20.0	-	12.0	-
Total	1,000 l	2,355.4 kg	1,000 l	2,338.2 kg

Table 3: Selected fresh concrete properties of Mix A and Mix B

Fresh concrete property	Mix A	Mix B
V-Funnel time [s]	11.8	5.2
V-Funnel time $_{5\,min}$ [s]	14.0	5.3
Stability time [s]	2.2	0.1
Slump flow [mm] [*]	730	820
Slump flow with J-Ring [mm] [*]	590	780
J-ring step [mm]	7.8	0.5
t_{50}-time [s] [*]	4.0	2.0
t_{60}-time [s] [*]	6.5	-
Fresh concrete temperature [°C]	22	24
		[*] the inverted cone method was applied

Table 4: Strength development of Mix A and Mix B

Compressive strength $f_{c,cube}$ in N/mm^2 after day	Mix A	Mix B
1	22.27	-
3	-	19.03
7	50.94	22.25
28	57.82	33.32

From Figure 4 it can be seen that Mix B, containing high volumes of the marble waste powder, is achieving medium strength while applying only 200 kg of cement. For Mix A a notably higher strength was obtained, in line with the use of 300 kg of the same cement type. This Mix also shows notable early strength of 22 N/mm^2 after one day.
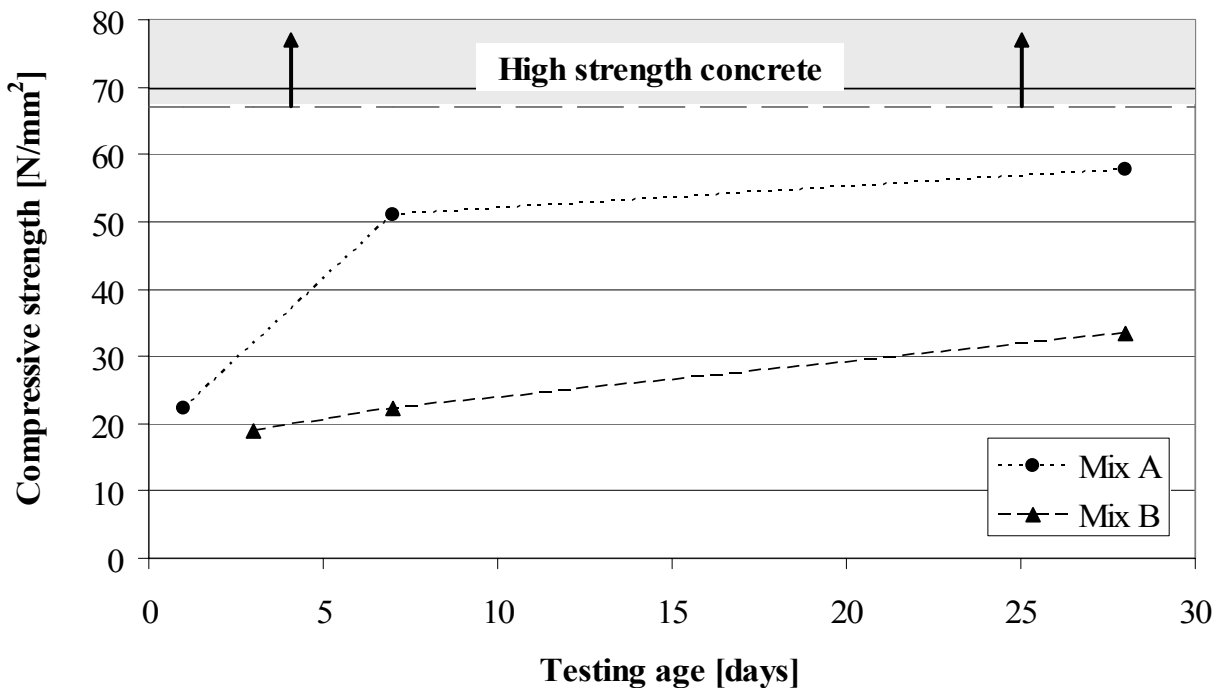
Figure 4: Mean compressive strength development for Mixes A and B, based on cube strength. For comparison the lower limit of high strength concrete ($f_{c,cube}$ = 67 N/mm^2) according to EN 206-1 is given.

5   Conclusion

This paper addresses a new and innovative mix design tool for the needs of SCC. Previous research has shown that this model can be successfully extended to conventionally vibrated concrete (CVC) and Earth-Moist Concrete (EMC). Based on the granular distribution the available material percentages are optimized according to a target distribution. Optimum use can be made of the starting materials. Therefore, this model is particularly suitable for the application of fine rock waste materials. The presented mixes demonstrate that natural stone waste powders can successfully be applied to SCC mixes, which partly possessed excellent self-compacting properties. A slightly worse behavior of mixes with the granite powder can be explained by the particle shapes as explained above. High amounts of deployed rock wastes and low amounts of cement make all these SCCs economically interesting, and environmental friendly. Waste material with no mass application is utilized, and energy consumption and CO_2-emission during cement production are prevented owing to notably lower cement dosages. Despite very low cement percentages the obtained mixes achieve medium strength. Mix A (C45/55) would

already be a high strength concrete according to the American nomenclature, which demands a minimum characteristic cylinder strength of 40 N/mm^2. Even Mix B with only 200 kg of cement and a corresponding strength class of C25/30 would be suitable for most of the structural demands in construction industry. Hence, the new design tool enables that cement can be used more efficient than it has been done so far. In other words, the herewith presented SCC mixes show equal or even lower production costs compared to standard concrete. Therefore, this type of SCC appears to be of interest for medium strength applications as well.

Another interesting observance concerns the appearance of the produced concrete. Fine powders significantly affect the concrete appearance, especially the color. Mix B with low cement content, coming along with a high load of purely white marble, resulted in an attractive bright concrete surface. Combined with the high surface quality of SCC this resulted in a highly esthetic concrete.

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