Study on resource conservation

High-performance concrete with natural fine sands as an alternative valuable aggregate

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"The global construction boom has triggered a shortage of sand. According to a recent UN report, the associated consequences for the environment are dramatic. Latest studies show that the demand for sand and gravel has tripled in the past 20 years. The UN Environmental Programme (UNEP) in Geneva considers sand, which is consumed at a rate of 40 to 50 billion tons per year, one of the most important traded raw materials worldwide. According to UNEP, unregulated sand mining harms the environment and rivers, deltas and coasts are being washed out, and sand mafias are flourishing, all while the demand is increasing. The main reason for the high demand is the increase in global construction activity. Sand is used alongside water, cement and gravel as an essential component for concrete production." [1]

Aggregates for normal and ultra-high-performance concrete

Concrete aggregates have to meet high demands in order to contribute to an optimal mineral grain structure once embedded in the solidified cementitious binder matrix. In addition to a favourable non-flaky shape and a grading curve selected for the particular application, aggregates should be dense, alkali-resistant, and frost-resistant. In high-performance concretes, the latter requirement can be achieved with a matrix of very low permeability, as experiments with granodiorite as aggregates in Ultra High-Performance Concrete (UHPC) at the University of Weimar have shown in the year 2012, where samples were submerged in water and NaCl solution and exposed to cyclic climatic exposure conditions for one year [2].

But also granulometry and grain shape of the aggregate are by far not as important for high-performance concretes as for normal concrete, since the concrete structure is actually different. Due to high and very high cementitious binder contents, a grain framework of sharp-edged cubic aggregates in coordinated grain sizes is not necessarily required here. Rather, the aggregates act as a filler, in a similar way as aggregates contribute to the mechanical strength of synthetic resins. In the case of UHPC, a binder combination of cement and fine pozzolanic minerals together with aggregates of grain sizes less 1 mm produce a very dense paste structure. Here, a good grain size distribution can also be useful for very high compressive strengths [3].

Fig. 1: Dyckerhoff gravel quarry in Seltz, France

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However, UHPC is only partially subjected to compressive forces and rather exposed to bending and tensile stresses. Consequently, the recommendations (Leaflet 2052) for Ultra-High-Performance Fiber Concrete of the Swiss Association of Engineers and Architects only requires a minimum compressive strength of 120 N/mm² for all performance classes, which is more than sufficient for practical applications. This strength can also be achieved without selecting a specific aggregate grading curve, whereas for the more important high flexural tensile strengths, a single industrially processed sand with grain sizes of 0.063-0.25 mm is sufficient [4].

High-performance concretes are currently still used in very special applications and are associated with high costs per cubic metre. With a mass of the building components that is sometimes reduced by up to 50%, however, a much more positive picture emerges and if aspects such as CO_2 emissions and raw material consumption are also considered, building with high-performance concrete can become very attractive.

Fig. 2: Dyckerhoff Gravel Plant Trebur, Germany

Fig. 3: Desert sand

Fine aggregates that are unsuitable from a concrete technology perspective

"Due to the worldwide lack of suitable sands for concrete production, previously unused resources such as desert sand or fine sands are increasingly coming into focus. So far, the fine sand fractions contained in the sand have mostly been separated and discarded. In Germany alone, the proportion of fine sands that has not yet been used and thus deposited amounts to up to 40 million tonnes per year. In addition, the deposited fine sands cause considerable environmental damage. The grain structure of fine sands and desert sands is characterized by a rounded geometry and a smooth surface. Due to this nature, fine sands and desert sands are unsuitable for the production of concrete." [5]

"Desert sands or Aeolian sands differ significantly from river sands and sea sands due to their history of origin. In particular, they are characterized by a very round grain shape with smooth surfaces and a narrow grain gradation. Measured grain densities of desert sands are usually between 2.44 and 2.87 kg/dm³ and particle sizes range between d = 0.04 to 0.80 mm, whereby up to 8% of these sands can have a grain diameter of less than 0.07 mm. It has been observed that these values differ only slightly between geographically distant regions. Desert sands are therefore not suitable for replacing river sands simply because of their grain size distribution. The tight grading curves also result in a lack of packing density. Another obstacle is the insufficient grain-to-grain support due to the smooth surfaces and the round grain shape." [6]

The main properties that make these sands less suitable for concrete production are therefore grain shape and gradation, as well as the fineness of sands with < 1 mm particle size. For the production of ready-mixed concrete, usually only sand 0/2 mm is used. Sands 0/1 mm as well as mud sand from the washing of gravel are abundantly available in Europe.

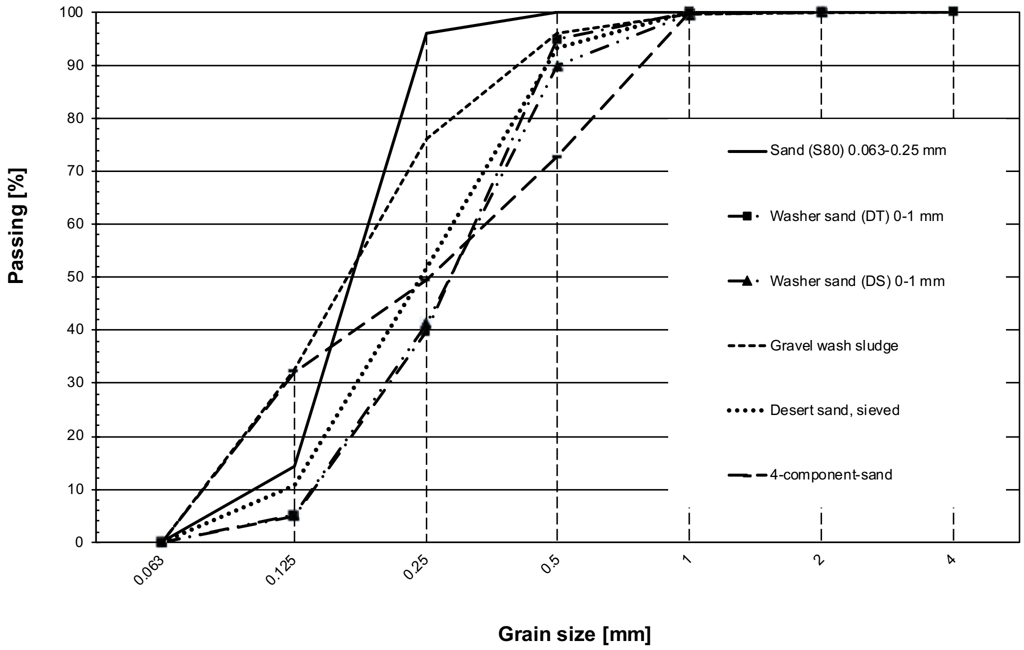

Fig. 4: Grading curves of natural fine sands for UHPCs

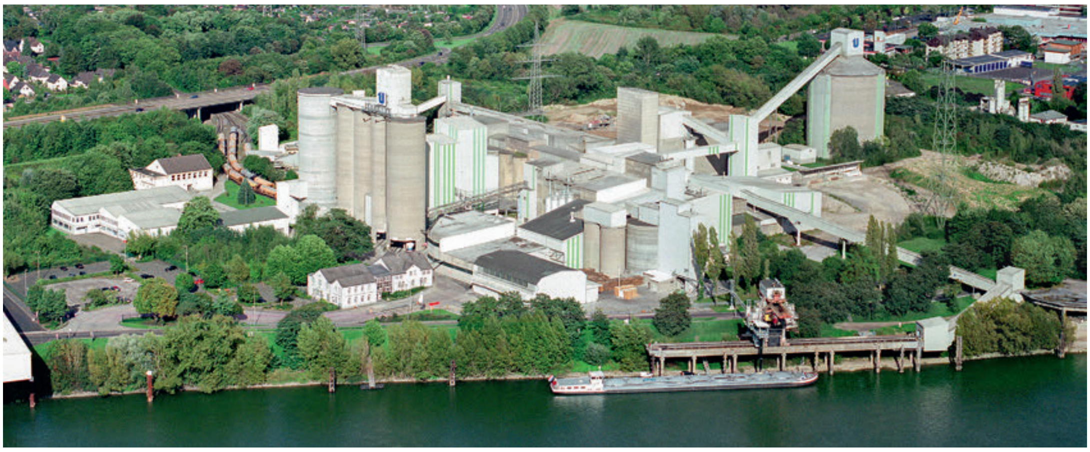

Fig. 5: Dyckerhoff cement plant in Neuwied, Germany

In Middle Eastern regions, desert sand is widely available. The mineral basis of the fine sands is usually quartz and therefore they are well suited as fillers for UHPC mixtures. The grading curves of these sands are all mostly in the range between 0.063 and 0.5 mm (Fig. 4).

Cementitious binders for high-performance concretes

In addition to the usual combinations of Portland cement and finely ground pozzolans [3], ready-to-use special building materials based on cements of high fineness have been produced at the Dyckerhoff Neuwied plant for over 20 years [4]. Nanodur Compound 5941 contains 41% quartz sand and 59% cement based on standard and fine cements as well as synthetic oxides. The binder premix has for more than 10 years been successfully used for the construction of machine beds and tool frames. Outside of Germany, the products have also been used in larger construction projects, which would in Germany only be possible with a general building authority approval. Also, the entire construction technology based on high-performance concretes in Germany is still waiting for a general regulation by the building authority, which, once established, will only include standard products.

Table 1: UHPC mix compositions

UHPC-mixes		NC 5941		Variodur 40							
VARIODUR 40 CEM III/A 52,5 R	kg/m^3	-	-	*900*	**9 0 0**						
Nanodur Compound 5941	kg/m^3	**1 7 0 0**		-	-	-	-	-	-	-	-
Sand (S80) 0.063-0.25 mm	kg/m^3	-	-	*1.230*	-	-	-	-	-	615	-
Desert sand, sieved (WSg)	kg/m^3	-	-	-	-	-	-	-	1.230	-	-
Gravel wash sludge (KWS)	kg/m^3	-	400	-	-	-	-	1.230	-	615	-
4-component-sand (4-K-S)	kg/m^3	-	-	-	-	-	-	-	-	-	1.230
Washer sand (A) 0-1 mm	kg/m^3	400	-	-	1.230	-	-	-	-	-	-
Washer sand (DT) 0-1 mm	kg/m^3	-	-	-	-	1.230	-	-	-	-	-
Washer sand (DS) 0-1 mm	kg/m^3	-	-		-	-	1.230	-	-	-	-
Micro steel fibres 12.5 / 0.175	kg/m^3	**2 0 0**									
PCE admixture	kg/m^3	20.0	22.6	25.0	22.0	18.5	18.9	24,0	16.5	21.6	21.6
Water (incl. water contained in PCE)	kg/m^3	235	235	196	180	180	180	207	180	193.5	193.5
w/b ratio	-	0.235	0.235	0.22	0.2	0.2	0.2	0.23	0.2	0.215	0.215
Slump flow (with impact)	mm	490	490	450	505	650	565	535	620	565	630
Hardened concrete properties, 28 days											
Compressive strength, prism	N/mm^2	169	182	191	195	204	187.8	174	208	186.6	210.1
Compressive strength, cube	N/mm^2	150	142	157	157	163	149	150	160	154.1	175.9
Compressive strength, cylinder	N/mm^2	-	-	145	-	-	138.85	-	152	145.5	163.7
Modulus of elasticity	N/mm^2	-	-	43.900	-	-	43.133	-	47.262	45.361	47.808
4-point flexural strength, beam 40 x 100 x 500 mm^3	N/mm^2	-	-	22.0	-	-	22.2	-	-	-	-
4-point flexural strength, prism 40 x 40 x 160 mm^3	N/mm^2	17.8	20.4	18.4	18.7	19.3	20,0	17.4	17,0	17,0	16.4
Total porosity	Vol.-%	-	-	8.3	8.6	-	-	-	-	-	-

Variodur 40 CEM III/A 52.5 R is such a standard cement based on microdur technology, which will then no longer require any special approval. Ultra-high-strength concrete for particularly CO$_2$-efficient, slender building components can thus be produced without finely ground pozzolans, using common concrete mixing technology in precast and ready-mixed concrete plants [7].

Natural valuable fine sands as alternative aggregates

The first test to determine the basic suitability of alternative aggregates was carried out with only 400 kg/m^3 of washer sand and 1,700 kg/m^3 of Nanodur Compound 5941, i.e. the UHPC mixture contained a total of 1,000 kg/m^3 of cementitious binder and 700 + 400 = 1,100 kg/m^3 of quartz (fine) sand. Due to the good results, this first test was then repeated with 400 kg/m^3 of gravel wash sludge from the backwash pit of a gravel plant.

In principle, the scatter in test results obtained with high-performance concretes is quite large, whereby the condition of the test specimens, the specimen shapes, the filling behavior and compaction, etc. can affect the results.
The compressive strength measured on cubes (100 x 100 x 100 mm^3) of the two Nanodur variants were in the range of 150 N/mm^2 and considering the results obtained on prisms (40 x 40 x 160 mm^3), the gravel washing sludge was even slightly better than the washer sand 0/1 mm.

The UHPC formulation from the Dyckerhoff product information with 1,230 kg/m^3 of industrial fine sand S80 and 900 kg/m^3 standard cement Variodur 40 CEM III/A 52.5 R [8] was then taken as the reference for all further tests.

As a result, on average, all three washer sands 0/1mm showed a very high bending tensile strength of 19 N/mm^2, prism compressive strength of 195 N/mm^2, and cube compressive strength of 155 N/mm^2. Results of this magnitude were to be expected, as all grading curves were similar (Fig. 4). Other characteristic values such as modulus of elasticity and cylinder compressive strength of a concrete containing an exemplary tested washer sand 0/1 were also at a very high level and corresponded to the reference with the industrial fine sand S80. The results with gravel washing sludge showed slightly lower flexural tensile strengths at comparable compressive strengths.

A natural desert sand, sieved and purified for use in terrariums [9], shows grain shapes similar to those of gravel wash sludge and washer sand 0/1 mm (Fig. 6) and has particle sizes

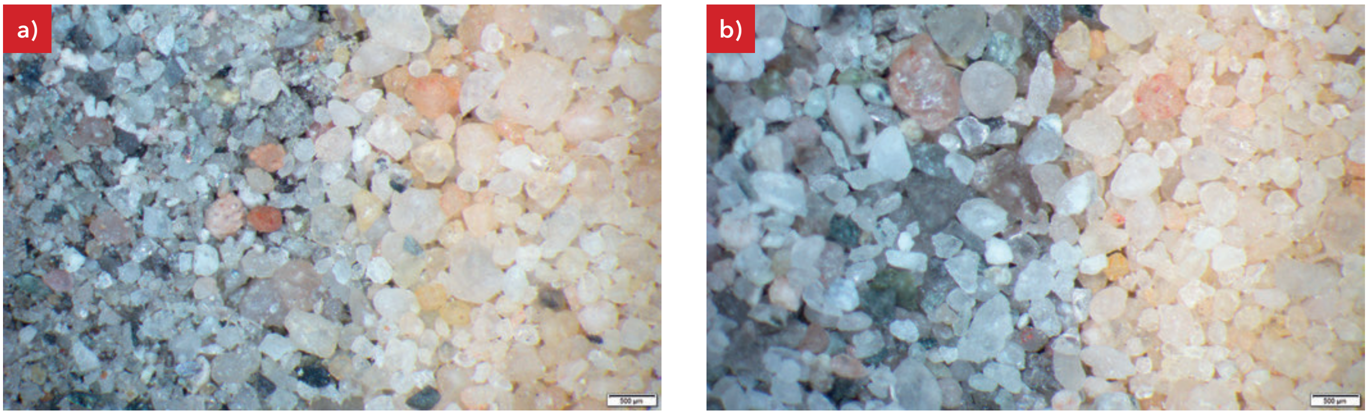

Fig. 6: a) KWS – Desert sand, b) Washer sand 0/1 – desert sand. (Microscopic images with 18x magnification)

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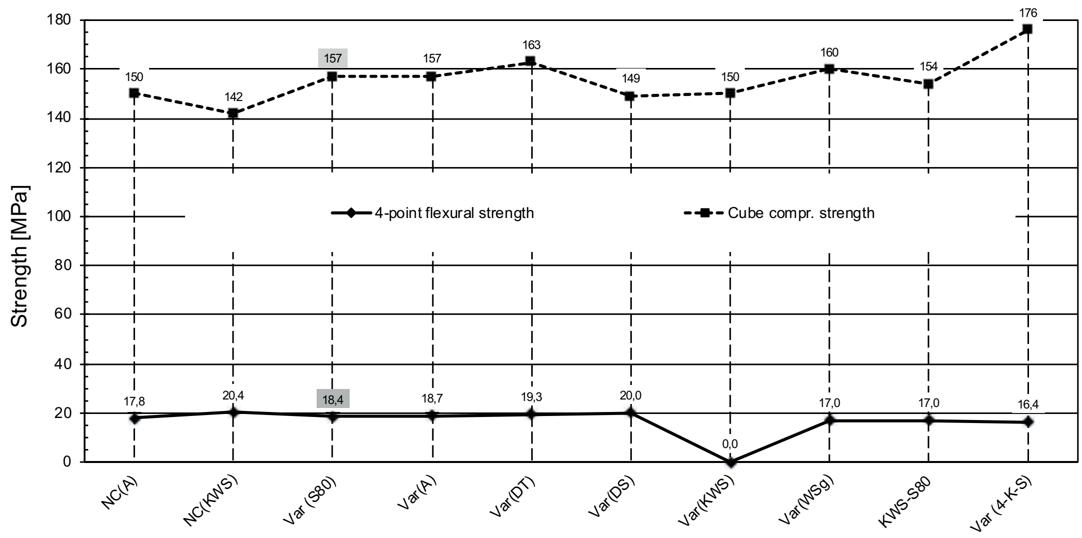

Fig. 7: Strength results of the tested concretes

in the previously described grain size range between 0.04 - 0.8 mm [6]. The concrete cube and cylinder compressive strengths as well as the modulus of elasticity were comparatively high here, but the flexural tensile strength was somewhat lower.

Finally, a mixture of 50% industrial sand S80 and 50% gravel washing sludge as well as a graded sand formulation consisting of 4 components were tested analogously [3]. While the 50:50 mixture was at the level of the individual components in terms of compressive strength, the 4-component sand mixture showed significantly higher values. However, the flexural tensile strengths of the last two formulations were at a lower level. Here, too, special grain grading curves have not affected the bending tensile strength, which is more important for UHPC, but only lead to an increase in compressive strength, which is high already. This is once again confirmed by the many years of experience with UHPC in the field of machine beds and tool frames.

Conclusions and outlook

The results show that the mechanical properties of all variants with the alternative fine sands are at a very high level with > 140 N/mm² compressive strength and ≥ 17 N/mm² bending tensile strength. This supports the hypothesis that high-performance concrete with a very high-quality cementitious binder matrix does not require any special quality and grading of the aggregate and that the aggregate is mainly to be regarded as a filler.

As a result of the dense UHPC matrix, the organic matter contained in the gravel washing sludge with 0.17 TOC compared to an average of 0.04 TOC for the washer sands also showed no serious effects. A test for clay components resulted in 0.15 g/100g in a methylene blue solution for the washer sands and gravel washing sludge and was therefore not critical.

In principle, it is possible to produce high-performance concrete using Nanodur Compound 5941 as well as with standard cement Variodur 40 in combination with the fine materials from sand and gravel processing, which are otherwise not suitable or only partially suitable as fine aggregates in concrete. Used in isolation, the least favourable results are expected with these fine materials, while combinations with higher quality aggregates can only improve the results.

High-performance concrete could therefore make a significant contribution to resource conservation, in addition to being significantly more CO_2-efficient than normal concrete, which is related to the smaller required component dimensions. ■

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