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## Original Research Paper

# Measurement of particle size distribution and specific surface area for crushed concrete aggregate fines

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### ABSTRACT

Different methods for measuring particle size distribution (PSD) and specific surface area of crushed aggregate fines ( $\leq 250 \mu\text{m}$ ), produced by high-speed vertical shaft impact (VSI) crushing of rock types from different quarries in Norway, have been investigated. Among all the methods studied, X-ray sedimentation is preferred because it has adequate resolution and requires fewer and more reliable input parameters. This combination makes it suitable for practical applications at hard rock quarries. X-ray microcomputed tomography ( $\mu\text{CT}$ ) combined with spherical harmonic analysis was applied to estimate the actual error introduced when PSD measurements were used to calculate the specific surface area of the VSI crushed rock fines. The  $\mu\text{CT}$  results, to the limit of their resolution, show that the error in the calculated surface area caused by assuming spherical particles (a common assumption in PSD measurements) is of unexpectedly similar magnitude ( $-20\%$  to  $-30\%$ ) over the entire investigated particle size range, which was approximately  $3\text{--}200 \mu\text{m}$ . This finding is important, because it simplifies relative surface area determination and is thought to be quite general, since the crushed aggregate fines investigated were produced from 10 rock types that had a wide range of mineralogies.

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## 1. Introduction

The concrete aggregate industry has historically limited particle size distribution (PSD) analysis, for fine particles, to simply determining the mass fraction of particles passing a sieve with square openings of minimum edge length  $0.063 \text{ mm}$  (according to EN 933-1 [1]) or  $0.075 \text{ mm}$  (according to ASTM C136 [2]). The European industry standard method intended for analysing the grading of filler aggregates, namely EN 933-10 [3], is similar. This standard only describes a method of more precisely determining the amount of particles that are smaller than  $0.063 \text{ mm}$ , but not differentiating the particles beyond that. On the other hand, natural and manufactured concrete fine aggregates (sand) have been reported to include particles down to the sub-micrometer size range [4–7].

The importance of a more detailed fine particle analysis has become more evident during the last few decades, with the need to replace the use of depleting natural sand materials, which normally contain little of the fine material that passes a  $0.063 \text{ mm}$  sieve, with manufactured crushed sands that generally include a much higher fine material content [8]. Accurate determination of the particle size distribution (PSD) of this material in the size range  $\leq 0.063 \text{ mm}$  is expected to provide valuable information for concrete proportioning [4,5,9–11,6]. Fines have a significant influence on most concrete properties, both in fresh and in hardened concrete. The PSD and specific surface area are the main parameters used to describe fines. Furthermore, the influence of fines is even more pronounced for modern high-workability concrete such as self-compacting concretes [11,6,7].

As there is no standard procedure covering the whole range of concrete aggregate PSD, different researchers [12,4,13,10,14,5,11,6,7] have used widely different measurement methods. It is, however, well-established from research within the geological sciences on analysing natural sediments of similar grain size distributions [15–18] that different measurement methods can yield

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**Table 1**  
Crushed rock fines used for the study.

Rock type		Mylonitic quartz diorite	Gneiss/granite	Quartzite	Anorthosite	Limestone	Limestone	Dolomite	Basalt	Aplite	Granite/gneiss
Rock type designation		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Fraction	Nominal size <sup>a</sup> [μm]	Designation of crushed aggregate fines									
Fine	4–25	T1-1	T2-1	T3-1	T4-1	T5-1	T6-1	T7-1	T8-1	T9-1	T10-1
Medium	20–60	T1-2	T2-2	T3-2	T4-2	T5-2	T6-2	T7-2	T8-2	T9-2	T10-2
Coarse	40–250	T1-3	T2-3	T3-3	T4-3	T5-3	T6-3	T7-3	T8-3	T9-3	T10-3

<sup>a</sup> The nominal size is approximate given in terms of the  $d_{10}$  and  $d_{90}$  diameters, which means that each size range can include up to about 10%, by mass, smaller and larger particles.

**Table 2**  
Mineralogical composition of 4–25 μm powder fractions determined with quantitative XRD.

Rock type	Mylonitic quartz diorite	Gneiss/granite	Quartzite	Anorthosite	Limestone	Limestone	Dolomite	Basalt	Aplite	Granite/gneiss
Rock type designation	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Tested fraction	4–25 μm									
Mineral or group of minerals	Mass %									
Quartz	27.9	20.9	90.0	6.5	2.3	2.5	1.1	8.9	36.2	17.8
Carbonate minerals	4.4	–	3.6	10.6	97.7	95.0	95.0	8.3	–	5.0
Epidote minerals	8.4	–	–	24.4	–	–	–	7.6	–	–
Feldspar minerals	37.7	63.9	3.9	33.1	–	0.4	0.6	26.5	58.2	58.8
Sheet silicates	8.0	8.1	1.5	20.4	–	1.5	0.7	5.2	2.7	9.2
Chlorite	11.3	1.4	1.0	2.6	–	0.6	1.6	20.2	1.7	0.5
Inosilicate minerals	1.0	3.9	–	2.3	–	–	1.1	11.0	1.2	8.7
Iron oxide minerals	–	–	–	–	–	–	–	3.5	–	–
Other minerals	1.3	1.9	–	0.2	–	–	–	8.8	–	–

83 very different results depending on the properties of the analysed  
84 materials. A recent study [7] suggested that this can also be true for  
85 crushed concrete aggregate filler materials. Therefore, a variety of  
86 measurement techniques has been investigated in this paper to  
87 better understand how the size and surface area of fine particles  
88 can be determined and how the results can be interpreted in terms  
89 of particle size, surface area, and shape.

90 **2. Materials and methods**

91 **2.1. Materials**

92 Fine aggregate powder (filler) materials used for the study were  
93 produced from 10 different blasted and crushed rocks with an  
94 original size range of about 4–22 mm. Further processing included  
95 Vertical Shaft Impact (VSI) crushing to generate fines and air-  
96 classification into three distinct size fractions with approximately  
97 the following  $d_{10}$  to  $d_{90}$  ranges: 4–25 μm, 20–60 μm and  
98 40–250 μm (Table 1). The size parameter  $d_N$  is the maximum  
99 diameter of the smallest N % of the particles by mass. Thirty differ-  
100 ent fine powder samples were produced: three particle size ranges  
101 for each of the 10 rock types with different mineralogical composi-  
102 tions (Table 2). The finest of powder fractions (4–25 μm) included  
103 all the particles smaller than 4 μm generated during the crushing  
104 and afterwards extracted by air-classification. Mineralogical com-  
105 position of the powders was determined by quantitative X-ray  
106 diffraction (XRD) analysis. The samples were first ground using a  
107 micronizing mill with agate grinding elements to a fineness of  
108  $d_{50}$  approximately equal to 10 μm, using ethanol as a grinding  
109 fluid, and subsequently dried overnight at 85 °C in a covered petri  
110 dish. After drying, the sample material was put in a poly(methyl

methacrylate) (PMMA) specimen holder following minor  
adaptations of standard procedures [19]. XRD data were collected  
in a Bruker<sup>1</sup> X-ray Diffractor D8 Advance, using 40 kV, 40 mA and  
Cu  $K\alpha$  radiation of wavelength  $K\alpha_1 = 0.15406$  nm and  
 $K\alpha_2 = 0.154439$  nm and a  $K\alpha_1/K\alpha_2$  ratio of 0.5. Diffractograms were  
recorded at diffraction angles ( $2\theta$ ) from 3° to 65°, in 0.009°  
increments with 0.6 s counting time per increment. The total  
analysis time per sample was 71 min. Further analysis was based  
on the X-ray powder diffraction results and the minerals in the ICDD  
database implemented in the software Bruker EVA<sup>®</sup>. The first step  
was mineral identification, and then the peaks of each mineral were  
scaled manually to give the best fit to the observed XRD  
diffractogram. The semi-quantitative mineralogy found based on  
 $2\theta$ -intensity data analysed by the XRD instrument was passed to  
the software Topas Rietveld XRD, which was used to perform a struc-  
tural refinement. The results of the analysis (Table 2) are provided  
only for the 4–25 μm fractions, but the mineralogical composition  
was in fact determined for all three size ranges of the fillers. The  
compositional variation among different particle sizes of the same  
rock type was relatively small, which is why all of the results have  
not been reported here. The uncertainty in the mineralogical compo-  
sitions presented in Table 2 is estimated to be about ±1.6% out of the  
mass% for a single mineral phase at the 95% confidence level, as also  
demonstrated for rock material by Hestnes and Sørensen [20]. The  
groups of minerals used in Table 2 can include up to three different  
individual minerals.

<sup>1</sup> Commercial equipment, instruments, and materials mentioned in this paper are identified in order to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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