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Crushed sand in concrete – Effect of particle shape in different fractions and filler properties on rheology

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A B S T R A C T

Studies of sand particle characteristics (shape, voids content, filler particle size distribution) and rheology of concrete (slump-flow, yield stress and plastic viscosity) show that the 0.125/2 mm particle shape and ≤0.125 mm filler properties are the most important factors for concrete workability when the sand grading 0/8 mm is kept constant. By normalizing the maximum variation of rheology (slump-flow value in mm) obtained in mixes where different size fractions are exchanged, the fraction ≤ 0.125 mm was found to have around 6–8 times larger effect on rheology per unit volume % exchanged, compared to the coarser sand fractions: ≤0.125 mm = 35.2 mm/%; 0.125/2 mm = 4.9 mm/%; 2/5 mm = 6.0 mm/% and 5/8 mm = 3.8 mm/%.

1. Introduction and background

The relevant properties of crushed sand are in general quite different from those of natural sand. The main differences are recognised to be the following [1]:

- particles of crushed sand are generally not as equidimensional or at least not as rounded as natural aggregates and of a rougher surface texture;
- fines[1] or filler content is normally much higher in crushed sand compared to natural sand;
- in a log (size) vs. linear (volume passed) graph the particle size distribution (PSD) is generally parabolic, or "dense" (resembling the parabolic maximum density grading curves as introduced by Fuller and Thomson in 1907 [4] and further interpreted by others [5]); while grading of a typical natural sand in the same coordinates is straight or very often "S-shaped";
- crushed sand produced from hard rock generally has lower variation in mineralogy, and the surfaces are less weathered than natural sand.

The first three differences are thought to be the main reasons why worse workability is observed, when different crushed sands are compared with natural sands for their performance in fresh concrete [6–11]. In particular problems with concrete rheology are observed if crushed sand simply replaces natural sand with no special adjustments of either particle size distribution or mix design. From the aforementioned it is also obvious why most of the attempts to increase the quality of the crushed sand are aimed at improving particle shape, decreasing total fines content and adjusting the grading. Different techniques for that are available already today, such as the vertical shaft impact (VSI) rock-on-rock

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[1] The particle size definition of fines is diverse. According to the EN 12620 [2] fines are all material less than 63 μm. ASTM standard C33/C33M – 13 [3] has a similar limit of 75 μm. For practical concrete purposes (see the Particle-Matrix proportioning method below) in Norway it is most common that all material less than or 125 μm is referred to as fines. The practical definition of crushed aggregate fines <125 μm is then used in this paper and we also used the terms filler and powder instead of only fines.

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crushers for improving the particle shape and dry or wet processing techniques (air-classification and washing) for fines removal [11–18]. However, these technologies can be expensive and make it difficult to achieve good mass balance (ratio between the produced and sold fractions). On the other hand, there are studies [19–24] that suggest that not all aggregate particle sizes have an equal relative effect on the fresh concrete rheological properties. Thus not all of them might need equal care with respect to assuring good grain shape or other relevant properties. Identifying the relative separate importance of different sand size fractions on fresh concrete rheological properties would broaden the knowledge of the "aggregate properties-concrete rheology" relationship. It would also give a better idea about how to approach the question of crushed sand production into a more economical and sustainable manner, because efforts for improvements of the sand quality could be aimed at parts of the grading where they would yield the maximum result.

The effect of different aggregate size fractions on the rheological properties of concrete has been previously studied by Wills [19]. Wills [19] has studied different fine and coarse aggregates from nine sources. He found that an equal change in shape characteristics caused fine aggregates to increase the water demand of the mix two to three times more than the coarse aggregate. This has recently been verified once again by Koehler on Fowler [24] for modern self-compacting concrete (SCC) with polycarboxylate based superplasticizers (SPs). These findings are also approved by the general concrete production practice of Norway today where the use of crushed sand in concrete is not as straight-forward as replacing coarse natural gravel aggregate with crushed coarse aggregate. The latter is known to only slightly increase the water demand of the mixes, unless shape of the coarse aggregate is very poor, i.e. elongated, flaky or otherwise strongly non-equidimensional. Coarse crushed aggregates are therefore widely used in a combination with natural sand. However, for the finest or sand-part of the aggregate (≤8[2] or 4 mm) it has proved to be a lot more challenging to use crushed materials. Many Norwegian concrete producers have found that the use of mass fractions from 10 and up to 50% of the total sand content may give rather good fresh concrete rheological properties. But the final step – to use 100% crushed sand is still rather challenging.

The reason why different aggregate size fractions affect the rheology of the fresh concrete in a different way can be attributed to two known phenomena. The first can be found among the fundamental findings by Krieger and Dougherty [25], who proved that the effect of mono-sized sphere particles on the flow (viscosity) in a concentrated suspension will strongly depend on their normalised solid concentration, *i.e.* the maximum packing fraction φ/φ_m (where φ is solid concentration and φ_m is the maximum solid concentration or maximum packing). The importance of this parameter has also later been verified for concrete [26]. φ_m depends mainly on two factors; particle size distribution and shape and thus a clear relation between these two and rheology is established.

Another relevant characteristic, differing between different sizes of aggregate fractions, is their specific surface area. This is since the coarse aggregate particle size usually varies within a factor of not more than 10 (in Norway typically approx. 8–22 mm), while sand particle size varies in the order of 10^4 (approx. 8 mm–0.001 mm = 1 μm). Therefore, most of the specific surface in the aggregate is concentrated in the sand and especially the filler fractions, because the ratio of surface area to volume increase exponentially with decreased particle size [27]. This also means that any detrimental or undesirable shape or texture characteristics will be greatly amplified when the effect of sand and especially the filler properties on fresh concrete rheology is assessed.

In fact, already some of the available concrete proportioning methods recognize the different effect from different aggregate size fractions when fresh concrete rheological properties are considered. The importance of the surface-to-volume ratio in different fractions was first realized early in concrete proportioning by Heath [28] and further elaborated by Edwards [29]. Logics behind the specific surface proportioning method are that finer aggregate fractions (sand and filler) have a higher specific surface area and will therefore require a higher amount of cement and water to coat them. At first glance, this makes sense; however, the approach has proven not to represent the actual behaviour of fresh concrete rheology and has been reported not to be widely used [30]. This is since particles smaller than about 150 μm have been suggested to lubricate the mix by facilitating rolling and sliding of the larger particles over each other [30]. So if these particles sizes are present in sufficient, however, not excessive, amounts, they can actually reduce water requirement of a mix [30]. This was recognised by Murdock [31] who suggested an empirical "surface index" that would indicate the actual influence of each particle size group (related to performance in fresh concrete and not directly to the actual specific surface). This is illustrated in Table 1, and it can be seen that Murdock's "surface index" shows decreasing numerical values for aggregate sizes smaller than about 600 μm. The "surface index" approach seems to some extent to still work quite well for everyday concrete production also with the use of the modern SPs, and a concrete proportioning method that somewhat relies on the phenomena reported by Murdock has been elaborated by Mørtsell [20] and Mørtsell, Maage and Smeplass [21] also for concrete types including modern admixtures. It is called the Particle-Matrix concrete workability model for proportioning where all particles >125 μm are regarded as *particle phase* dispersed in lubricating *matrix phase* made up of all fluids (water, admixtures etc.) and particles (binder, filler etc.) ≤ 125 μm. Concrete flow is demonstrated to be dependent only on properties of the two phases and the volumetric relation between them [20,21]. The method has been used in Scandinavian countries (especially in Norway and Sweden) by many practitioners for almost two decades and has proven to be very useful.

Day [23] has also suggested modifications to the original specific-surface theory [28,29] by stating that: "The original SS [*specific-surface*] theory did not work in the practice because it was found to over-estimate the effect of very fine particles. … The author's modification recognises that, as diameter reduces, a point is reached where it takes less water to fill the voids than it does to fill its surface. (Italic text inserted.)" On the grounds of his statement Day [23] has introduced "modified specific surface" values as shown in the fourth column of Table 1.

For aggregate producers the requirement from the concrete industry and the standardisation [6,33,34] has normally been to reduce the total fines content of the crushed sand; usually to amounts only marginally higher than those found in the natural sand. However, several researchers [6,8,33] have found that much higher fines content would be desirable in the crushed sand for better performance in concrete. It is justified by the fact that more fines will fill in the voids between the more angular crushed sand particles [33] and provide additional lubricating effect (as originally discovered by Murdock [31]). Furthermore, some other results [20,24,35–37] have suggested that not only the total crushed fines

[2] According to EN 12620 [2] aggregates with $D_{max} \leq 4$ mm are classified as fine aggregate. The standard also defines a 0/8 mm naturally graded aggregate. However, due to the Norwegian traditional use of naturally graded 0/8 mm as fine aggregate, fractions ≤8 mm are often referred to as "sand" while fractions >8 mm are referred to as "stone".