Washing of Aggregates - Influence on Aggregate Properties and Mortar Rheology

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ABSTRACT

Aggregates (0-2 mm) produced by blasting and crushing of bedrock often contains rough and flaky particles with free mica and other minerals in finer fractions. Consequently, concrete produced with this type of aggregate displays a higher water demand and lower workability than the corresponding concrete with glaciofluvial aggregate. In order to achieve the desired workability changes in the mix design and/or processing of the aggregate, e.g. sieving and washing, are required.

In this paper, the effect of washing on the material properties, i.e., particle size distribution, specific surface area and sand equivalent value (SE-value), of aggregates from crushed bedrock has been studied. The effect of the washed aggregates on the water demand of mortars was also studied with rheological methods.

The results show that the used washing procedure mainly removed particles below 125 μm with emphasis on particles smaller than 40 μm. Consequently, this resulted in a decrease in the specific surface area of the fine particles and, thus, a lower water demand of the mortar. This is verified in the mortar tests where the yield stress of mortars was significantly reduced when the washed aggregates were used.

Key words: fine aggregate, specific surface, washing, rheology, mortar, sand equivalent.

1. INTRODUCTION

In Sweden, concrete has traditionally been manufactured with glaciofluvial aggregates. However the supply of this type of aggregate is unevenly distributed with scarcity in some regions. Since these remaining deposits are of importance for the water supply and also of natural and cultural value there is of interests to preserve them. Aggregate from crushed bedrock is an alternative to glaciofluvial aggregates. However, aggregate produced by blasting and crushing of bedrock often give rough and flaky particles with free mica and other minerals in the finer fractions. The amount of fine particles (<0.25 mm) is generally high; especially with fragile rocks such as granites that generates much more fines than mafic rocks like diabase and gabbro [1].

The generated fine particles may be of poor quality, e.g., flaky or of high specific surface area due weathering and clay alteration, or in excess amounts and are in those cases unwanted in concrete since they impair the workability and increase the water demand. One way to improve an aggregate with fine particles of poor quality is to remove this fraction and add a mineral admixture of suitable quality.

Screening is an extensively used method to size aggregate. However, the screening efficiency decreases rapidly with the fineness of the material [2], hence the potential of screening as a method to remove fine particles on an industrial scale seems to be limited. Sizing of material smaller than 0.25 mm is normally done by classification, which is based on the velocity differences of which the grains fall through a medium. There exist many types of classifiers which theoretically may be used to remove fine particles from crushed aggregates. In practice washing of aggregates is a common method used to remove fines from aggregates.

In this paper results from a study on the effect of washing on the material properties, i.e., particle size distribution, specific surface area and the SE- value, of aggregates are presented. Furthermore, the effect of washing on the water demand, i.e., rheological properties, of mortars was evaluated. In this part the remaining fine particles after the washing procedure was evaluated separately in micromortars.

2. EXPERIMENTAL

2.1 Materials

A portland-limestone cement, (CEM II/A-L 42.5 R), was used in these experiments. The cement contains approximately 13 percent limestone and has a specific surface area, according to the BET method, of approximately 1740 m^2/kg. The specific surface area expressed as Blaine is approximately 460 m^2/kg. The fineness of the cement is much given by the inter-ground limestone. The cement was delivered by the Swedish cement producer Cementa AB.

Six different aggregates (0-2 mm) were used of which five originate from crushed rocks (C3, C5, C7, C9, C18W). Five of the crushed aggregates originate from granitoid gneiss rocks (C3, C5, C7, C9) and one (C18W) from quartz sandstone. A glaciofluvial aggregate (N1), mainly of granite origin, was used as reference aggregate in the experiments. The aggregates were selected from a larger collection of materials included in a Swedish research program on the use of manufactured aggregate in concrete [3]. The selection of materials was mainly done on the basis of their material properties, i.e., particle size distribution and specific surface area, and performance in mortars. These properties have previously been described in [4, 5]. Aggregate C18W was selected since it was washed on-site and therefore could be used as a reference aggregate in the washing experiments in this work.

2.2 Methods

Washing procedure
The aggregates were washed in the laboratory by using a bucket and stirring machine. The washing procedure was as the following (Figure 1); the aggregate was suspended in water and agitated vigorously. Thereafter, coarse particles were allowed to sediment during a period of 30 seconds. After the sedimentation period the water phase containing suspended fine particles was decanted. The volume ratio between water and aggregate was approximately 3.5, thus, the aggregates were washed in large amounts of water. This results in an effective washing of the aggregates. The described washing procedure was performed two times on each aggregate.

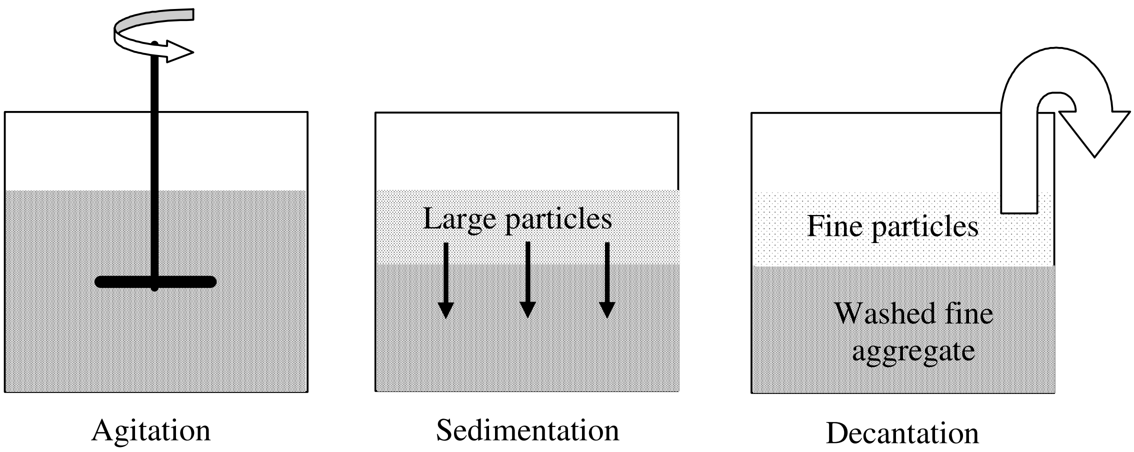

Figure 1 - Washing procedure

The washed aggregates were collected and dried in an oven at 105 °C. Thereafter, the aggregates were homogenized and samples were taken out for particle size analysis and specific surface area measurements. These properties were determined on both the washed and unwashed aggregates. The particle size distribution was determined both on the aggregate (0-2 mm) and on the fine fraction separately. In this work, fine particles are defined as particles smaller than 0.25 mm. The size distribution of the fine particles were determined with an instrument (Malvern Mastersizer) of which the measuring technology is based on light scattering/ diffraction.

The specific surface area of the fine particles was measured through nitrogen adsorption using BET theory. Both the particle size distribution and specific surface area of the fine particles were analysed at Cementa Research AB.

In addition to the mentioned analyses the SE-value of the aggregates was determined in accordance with the European standard, EN 933-8. The SE- test is a method for quality control of aggregates, which measures the quantity of unfavorable fine dust and clay, i.e., fines< 63 μm [6]. The principle of the method is the following: the aggregate sample and a deflocculation solution are poured into a graduated cylinder and irrigated to loosen the fines.

Thereafter, the sample is left for 20 minutes allowing non-colloidal particles to sediment, i.e., particles larger than approximately 10 μm. The SE-value is then calculated as the height of the sediment expressed as a percentage of the total height of the sediment and the suspended fines. A high SE-value value indicates that the quantity of fines in the analyzed aggregate is small while the opposite holds for low SE-values. For the time being there are no specified limits in the standard, but results from [7] shows on a drastic increase of the water demand, i.e., yield stress, as the SE-value falls below approximately 75 %.

Rheological measurements
The effect of washing on the performance of the aggregates in mortars was evaluated with a viscometer (Contec 4, ConTec Ltd.) suited for measurements on coarse particle suspensions, i.e., on suspensions with particle sizes up to approximately 16 mm. In addition, the fine particles were studied separately in micromortars in order to evaluate the effect of washing on their performance. The micromortars were studied with a viscometer (HAAKE Rotovisco CV20) adjusted for these types of suspensions [9].

Both viscometers operate according to the same principle and have measuring systems consisting of concentric cylinders. During a measurement the outer cylinder is rotated at different rotation velocities, thus shearing the sample at different rates of shear ($\dot{\gamma}$), while the inner stationary cylinder continuously registers the generated torque which is recalculated to shear stress (τ) with the Reiner-Riwlin equation [8]. The shear sequences which are used with the viscometers are well defined and have previously been described in [7, 9] for example. The registered data were analysed and the yield stress (τ_0) and the plastic viscosity (μ_{pl}) were calculated by applying the Bingham model (equation 1) to defined segments of the shear sequences.

$$\tau = \tau_0 + \mu_{pl} \cdot \dot{\gamma} \qquad (1)$$

The yield stress describes the required shear stress to initiate flow of the mortars, while the plastic viscosity describes how easily the mortar flows. Concrete with a low slump value can be considered as a high yield stress concrete, while self levelling concretes can be considered as the opposite. The viscosity is an important material property which describes the resistance towards flow. It can be considered as the internal friction of the mortar or concrete.

Viscometry is an excellent method to characterize cement-based materials since it describes the fresh properties with two parameters, i.e., yield stress and plastic viscosity, in contrast to e.g., the slump test which is a one point test. However, there are some potential sources of errors which need to be considered when measuring and evaluating the rheology. Segregation, equilibrium stress and plug flow belongs to these considerations. It is important that the sample remain its stability during the measurement since segregation results in a concentration gradient and, thus, influence the registered torque. It is also important to verify that the equilibrium stress at each rate of shear has been reached in order to avoid an overestimation of the shear stress. Plug flow may also occur in the gap between the cylinders at certain conditions and the phenomenon introduces an error in the measured yield stress and plastic viscosity of the mortar. However, according to [8] the error generated by plug is generally not a problem for mortars with $\tau_0/\mu_{pl} \leq 100$ s^{-1}. The error produced for $\tau_0/\mu_{pl} \propto 100$ s^{-1} is approximately 1 % for the yield stress and 10 % for the plastic viscosity. For the mortars evaluated in this paper the ratio between the yield stress and plastic viscosity were below 100

s^{-1} for all mortars except the ones with aggregate C7 and C9 of which the ratios were 138 s^{-1} and 119 s^{-1}, respectively.

3. RESULTS AND DISCUSSION

3.1 Effect of washing

Aggregate properties

The material properties of the aggregates, i.e., particles size distribution, specific surface and sand equivalent value, were measured prior to and after the washing procedure. The effect of washing on the particle size distribution of the aggregates can be seen in Figure 2. The results show that the used washing procedure primarily reduces the amount of material below approximately 0.125 mm. Furthermore, the results from the particle size analysis show that of this fraction only a smaller percentage (< 4.5 %) of the particles smaller than 40 µm remain after the washing procedure (Figure 3). The fine particles from aggregate C18W, which was washed by the aggregate producer on-site, showed a very similar particle size distribution as the laboratory washed, thus the results indicate that the used washing procedure give similar result as on-site washing. However, since the properties of aggregate C18W prior to washing were not available the differences in efficiency of the methods could not be evaluated.

The results show that washing seems to be an effective method to remove weathering clays or other unwanted fine particles, < 40 µm, from aggregates. On the other hand for aggregates containing large amounts of fine particles smaller than 0.25 mm, e.g., C3, sieving should be applied since washing only removes particles in size fractions below 0.125 mm.

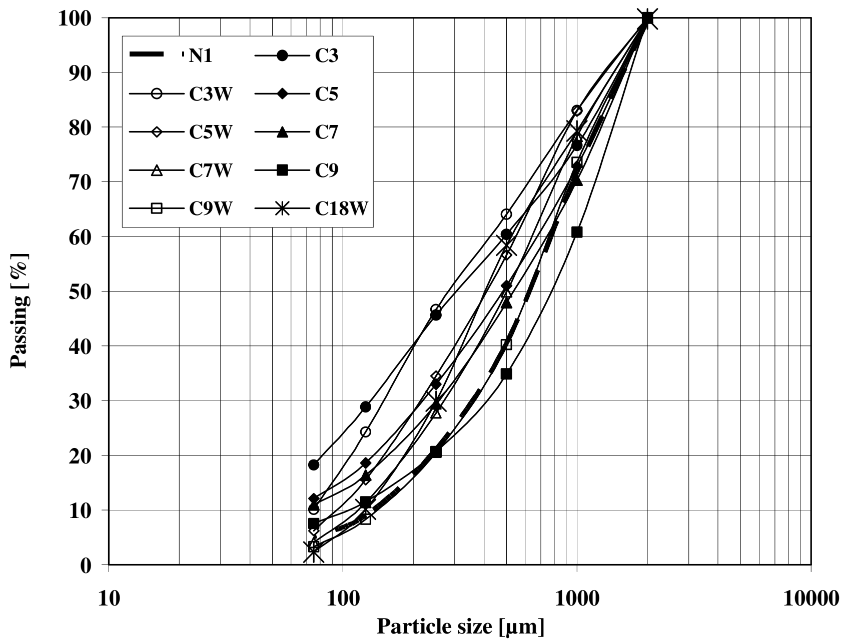

Figure 2 - Particle size distribution of unwashed and washed (W) aggregates.

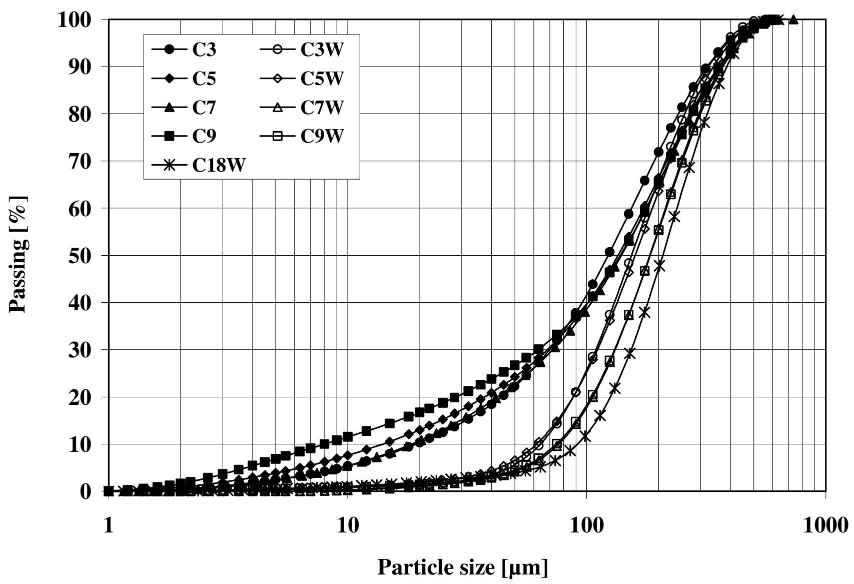

Figure 3 - Particle size distribution of the fine particles prior to and after washing.

A consequence of the removal of basically all fine particles smaller than 40 µm during the washing procedure is that the specific surface area of the fine particles is substantially reduced (Table 1). A reduction of the specific surface area implies that the required amount of water to wet the aggregate surface decreases and consequently also the water demand of the mortar or concrete. However, the fine particles from both aggregate C5 and C9 display relatively large specific surface areas despite the washing procedure. This indicates that these aggregates generally have a rougher surface texture. Furthermore, the fine particles from aggregate C9 contain high amounts of sericitized feldspar which displays a rough surface, thus contributing to the higher specific surface area. However, the rheological measurements (Figure 4 and Figure 7) indicate that the coarsest parts of (washed) C5 and C9 perform well, hence the specific surface area of the fine particles > 40 µm is of second order importance.

Table 1 - Sand equivalent value and specific surface area of the aggregates prior to and after the washing procedure.

Aggregate	SE- value [%]			Specific surface area [m^2/kg]		
	Unwashed	Washed	Δ [%]	Unwashed	Washed	Δ [m^2/kg]
N1	74	-	-	2650	-	-
C3	68	74	6	976	532	444
C5	68	79	11	2800	1810	990
C7	64	84	20	2490	828	1662
C9	41	88	47	4140	1330	2810
C18	-	91	-	-	960	-

In Table 1 the SE- values and specific surface area of the aggregates are shown. The SE- value of the unwashed glaciofluvial aggregate (N1) was 74 %. This aggregate has been used for concrete production over many years in Sweden and is well suited for this purpose. Therefore, a SE- value of 74 % is considered as a reference value of an aggregate with fines of good quality. In Saudi Arabia SE- value of 75 % is set as a limit for aggregates used in concrete for bridges and road constructions [6]. The SE- values of aggregate C3, C5 and C7 were between 64 % and 68 % while aggregate C9 displayed a very low value prior to washing. The fine particles from aggregate C9 contained the largest amount of ultra fine particles, <10 μm, and thus the highest specific surface area of all aggregates. The laboratory washed aggregates, and presumable the on-site washed, display significantly higher SE-values, ≥ 74 %, than prior to the washing procedure. From the table it can also be concluded that the change in specific surface area of the fine particles correlates well with the change in SE- value of the aggregate. This verifies that the SE- value mainly gives an indication on the quantity of ultra fine particles in the aggregate. It also shows that the method is suitable to detect variations in specific surface at site. In [6] the authors found a good correlation between the SE- value and the amount of material passing the 75 μm sieve. However, the conclusion was only valid for quartz sand and not for crushed aggregates. Furthermore, according to the result in [11] particles of clay size, i.e., < 4 μm, contributes strongly to the SE-value. A comparison of different amount of fine particles showed that only 6 % of bentonite was required to produce a SE-value of 30 % compared with 33 % of a quartz dust.

Rheological properties of mortars

The effect of washed aggregate (0-2 mm) on the rheological properties of mortars was studied with a Contec-4 viscometer. The mix design of the evaluated mortars is described in Table 2.

The constituents of the mortars were mixed for four minutes in a Hobart mixer equipped with a paddle stirrer. Immediately after mixing the mortar was transferred to the viscometer in which the rheological parameters were measured twice on each sample. Between each measurement the sample was homogenised manually by stirring with a trowel.

Table 2 - Mix design of the mortars.

Constituents	Amounts [g/l]
Cement	635
Aggregate, 0-2 mm	1148
Water	362
w/c	0.57
Vol.- % solids	0.64

Figure 4 shows the effect of washed aggregate on the rheological properties of mortars. The mortars with washed aggregate displays significantly lower yield stresses than the mortars with unwashed aggregate. This is a direct consequence of the removal of the very fine particles during the washing procedure. These particles contribute to the water demand through their large specific surface area and are also of such size that they may flocculate and immobilize mixing water under the influence of colloidal forces. Thus, the results show that the finest particles in the aggregates significantly influence the yield stress, and the water demand, of the mortars. The mortar with the on-site washed aggregate (C18W) showed almost identical rheology as the reference aggregate N1. This aggregate has similar particle shape as N1 which may explain the low viscosity.

However, the mortars with washed aggregate displayed slightly higher plastic viscosity than the mortars with unwashed aggregate (Figure 4). This is probably a result of increased particle interference due to the loss of fines in the washing procedure. The fines fill out the voids between the coarser aggregate particles and act as “lubricants” between them. Consequently, when the fines are removed the particle interference increases and consequently the viscosity. Another potential drawback of washing without addition of a supplementary powder is the increased risk of water separation due to lack of fines.

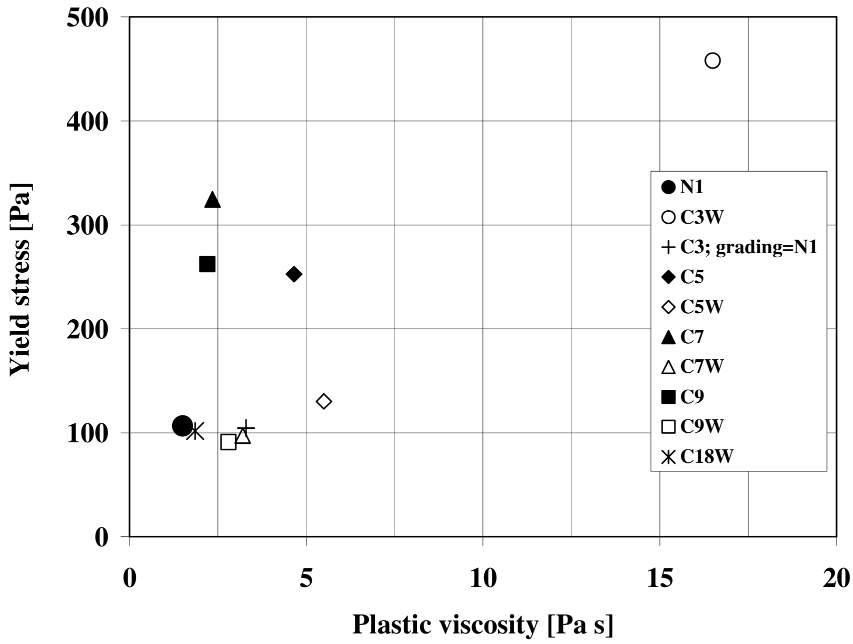

Figure 4 - Rheological properties of mortars with unwashed and washed (W) aggregate.

The mortar with unwashed aggregate C3 was too stiff to be measured in the viscometer. However, after the washing procedure the measurement could be carried out, even though the yield stress was relatively high. The high yield stress of this mortar is mainly due to excessive amount of fine particles, <0.25 mm), (Figure 2). The micromortar test also indicates this since both the unwashed and washed fine particles display yield stresses similar to aggregate N1 which performs well at moderate amounts. To confirm the results, the unwashed aggregate C3 was given similar grading (by sieving) as the reference aggregate N1, thus the amount of fine particles passing the 250 µm sieve was reduced by 25 % units. This action resulted in a substantial reduction in both the yield stress and plastic viscosity of the mortar (Figure 4). The yield stress was of the same order of magnitude as the mortar with the reference aggregate N1, while the plastic viscosity was higher. The higher viscosity is a result of increased particle interference due to the relatively large amounts of flaky particles in all size fractions of this aggregate [7]. The flakiness may also explain the higher viscosity of the micromortars. These results stress the importance of the overall grading of the aggregate with respect to the rheology and water demand of mortar and concrete.

From the results it can also be concluded that for the mortar with washed aggregates, the yield stress is largely related to the amount of fines< 250 µm sieve (Figure 5). Thus, the properties of the washed fine particles, i.e., specific surface area and surface chemistry, appear to be of minor importance. This clear relationship could not be observed for the unwashed aggregates which displayed large differences at similar amounts of fines. In this case the yield stress is largely influenced by the properties of the fine particles below 40 µm which was almost complete eliminated during washing. However, notice that there is no clear relationship between the specific surface area of the fine particles and the yield stress, hence other properties of the fine particles, i.e., surface chemistry and particle shape, contributes to the behaviour. The plastic viscosity of the mortar with washed aggregate is also large related to the amount of fine particles (Figure 6). However, the viscosity of the mortar is also related to the particle shape of the aggregate [7]. Some of the mortars fall out of the pattern, i.e., the mortars with C18W and N1 and C3 (grading=N1) of the unwashed aggregates, due to the shape of the aggregates. As mentioned above aggregate C18W has very good particle shape and C3 has poor shape which is reflected by the relatively low and high viscosity, respectively, of these mortars.

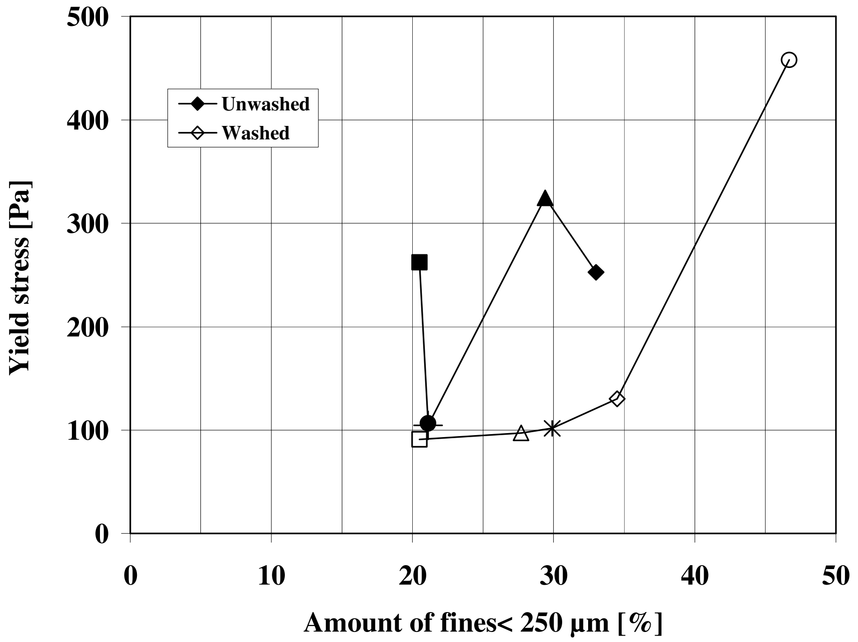

Figure 5 – Yield stress of mortars as a function of the amount of fines < 250 µm in the washed and unwashed aggregates. Filled and open symbols represents unwashed and washed aggregates, respectively. ✳=C18W, += C3; grading=N1.

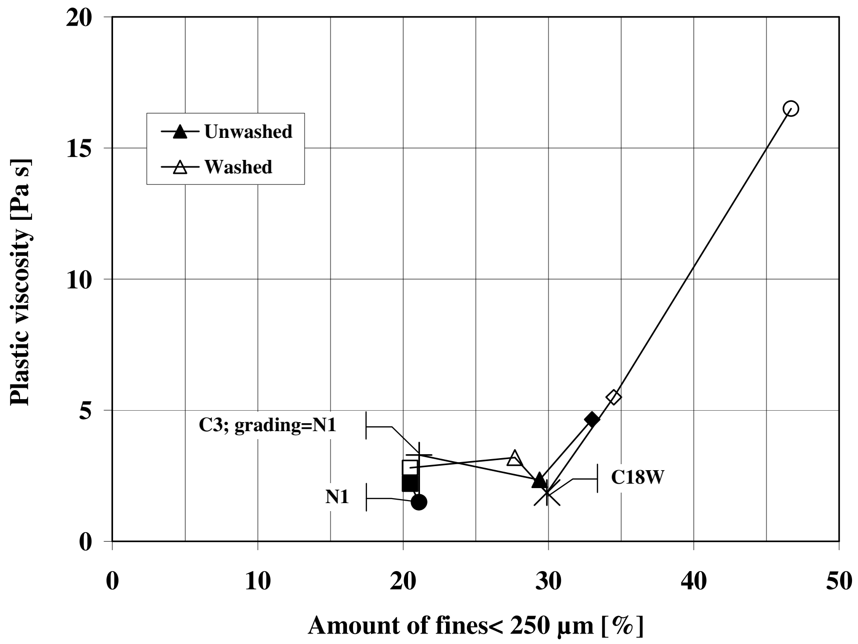

Figure 6 – Plastic viscosity of mortars as a function of the amount of fines < 250 µm in the washed and unwashed aggregates. Filled and open symbols represents unwashed and washed aggregates, respectively. ✳=C18W, += C3; grading=N1.

Rheological properties of micromortars

The fine particles from the washed aggregates were evaluated in micromortars with a HAAKE viscometer. In this investigation we only used fine particles< 0.25 mm, cement and water in the micromortars. This was done in order to evaluate the effect of the fine particles without any influence from admixtures, i.e., superplasticizer, etc. The mix design of the micromortars differs from the design of the mortars regarding paste volume and concentration of solids (Table 3). This is a consequence of the used method to design the micromortar and mortar. The concept of the mix design has previously been described in [10]. However, the differences are not of great concern in this study since the purpose of the micromortar tests solely was to evaluate the effect of washing on the performance of the fines fraction.

Table 3 - Mix design of the micromortars.

Constituents	Amounts [g/l]
Cement	828
Fines, 0- 0.25 mm	691
water	472
w/c	0.57
Vol.- % solids	0.53

The results from the rheological measurements on micromortars with washed fine particles are shown in Figure 7. In the figure the results for the unwashed fine particles are also included as references. Compared with the fine particles from the natural aggregate (N1) they display both larger plastic viscosities and yield stresses. The micromortar with fine particles from aggregate C9 was to stiff to be tested in the viscometer. However, it is expected to have higher values on the plastic viscosity and yield stress than micromortar C7.

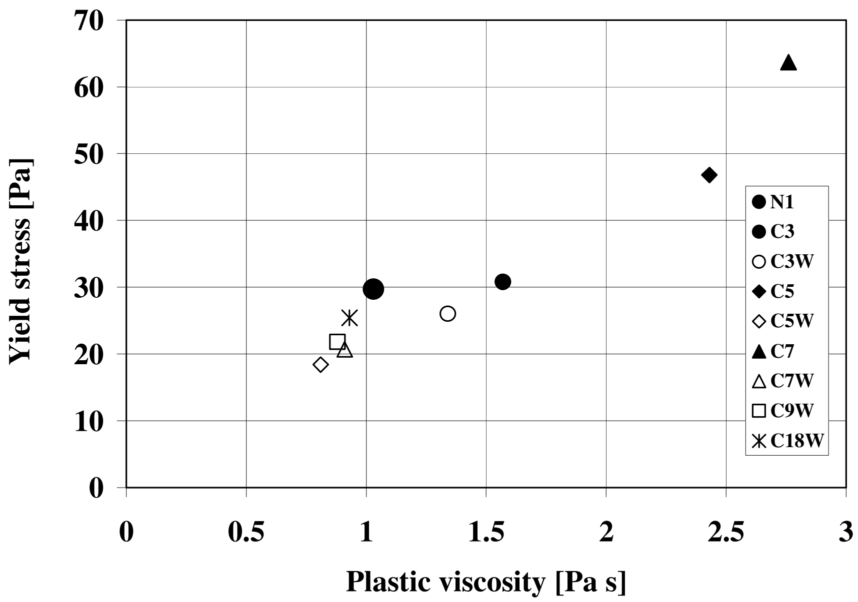

Figure 7 - Yield stress and plastic viscosity of micromortars containing unwashed and washed (W) aggregate fines.

The micromortars with washed fine particles displayed significantly lower yield stresses and plastic viscosities than the ones with unwashed fine particles. This is partly different from the mortars which displayed a large reduction in yield stress and a slight increase in viscosity. The different behaviour can probably be related to the mix design of the mortars, i.e., the differences in volume of aggregates and water. However, the largest change in rheology can be seen for the micromortars with fine particles from aggregate C7 and C5. They also displayed the largest change in specific surface area, i.e., of all fine particles that could be analysed in the micromortar (Table 1). The change in properties for the micromortar with fine particles from aggregate C9 could not be quantified, but should be in the same order or larger than the two mentioned micromortars. The largest reduction in specific surface area was observed for the fine particles from aggregate C9. The micromortar tests indicate that the high yield stresses of the mortars with aggregate C5, C7 and C9 (Figure 4) to a large extent originate from the properties of the fine particles in fractions below 40 µm.

The change in rheological properties of the micromortar with fines C3 was relatively small. These fines also showed the smallest change in specific surface area upon washing. Thus, the result further explains the relatively high yield stress and plastic viscosity of the mortar with washed aggregate C3 (Figure 4). That is, the washed aggregate C3 contains large amounts of fines, 47 % < 0.25 mm, with relatively high water demand.

4. CONCLUSIONS

This paper discusses the influence of washing on the material properties of aggregates and its effect on the water demand of mortar. The results show that the used washing technique primarily reduces the amount of material in size fractions below 125 µm with emphasis on particles smaller than 40 µm. Therefore, the method can be used to improve the properties of aggregates which contain fine particles of poor quality, e.g. weathering clays or badly shaped particles, in size fractions below 40 µm. However, the method is not selective in the sense that only fines of poor quality is removed, i.e., the fines are removed after size and not solely after quality. Furthermore, aggregates with particles of poor quality, e.g., high amounts of flaky micas, in coarser fractions require other actions to improve their suitability for concrete production.

Since the finest particles are removed in the washing procedure the specific surface area of the aggregates is significantly reduced and the SE- value increases. The change in specific surface area correlated with the change in SE-value which suggests that the SE-test can be used as a simple on-site test to detect variations in specific surface area.

The mortars with washed aggregate displayed significantly lower yield stress, or water demand, than the corresponding mortars with unwashed aggregate. This is a result of the removal of the finest particles which largely contribute to the water demand through their large specific surface area. However, the plastic viscosity of the mortars with washed aggregates was slightly higher than prior to washing. This is probably a result of increased particle interference and thus friction due to a deficit amount of lubricating fine particles. Furthermore, a clear trend between the amount of fine particles and the yield stress of the mortars was observed for the washed aggregates. This clear relationship could not be observed for the unwashed aggregates due to larger differences in properties of the fine particles.

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