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Influence of fine aggregate characteristics on the rheological properties of mortars

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Abstract

This paper presents results from a laboratory study on the influence of crushed fine aggregate on the rheological properties, i.e., yield stress and plastic viscosity, of the mortar phase of concrete. The effect of grading, particle shape, etc. of the fine aggregates has been evaluated with the use of a viscometer suited for coarse particle suspensions. The evaluation has been done at different dosages of superplasticizer and paste volumes by the use of an inert artificial "cement paste".

The results show that the properties and amount of fine aggregate have a strong influence on the water demand and workability of the mortar, i.e., the rheology. The large amounts of fines often found in crushed fine aggregate primarily increases the yield stress of the mortar. The amount of fines also contributes to the plastic viscosity by increased interparticle friction. However, the results clearly show that the particle shape of the fine aggregate strongly contributes to the plastic viscosity.

The influence of the properties of the fine aggregate is largely dependent on the paste volume of the mortar. Thus, by increasing the paste volume, negative effects of poorly graded and shaped aggregates can be eliminated or significantly reduced.

Keywords: Rheology; Aggregate; Particle size distribution; Particle shape; Sand equivalent; Mortar

1. Introduction

In Sweden most crushed rock is of granitic origin and there is a demand for using fine aggregate (0–4 mm) from this rock type in concrete. This fine aggregate differs from natural water sorted glaciofuvial fine aggregate in grading and particle shape. When the rock is blast and processed excessive amounts of fines is produced resulting in a fine aggregate with higher amounts of fines. Typically, between 10% and 25% of fines are generated during the production of fine aggregates [1,2]. The shape of the crushed fine aggregate is often more angular with rougher surfaces than natural fine aggregate which are rounder with smoother surfaces [1]. The fine particles are mainly granitoid rock minerals like feldspar, quartz and mica in different amounts. The natural aggregate is of similar origin but weathering has apart from rounding the particles changed the proportions and removed most of the weak minerals like the flaky micas. Due to these differences, concrete with crushed aggregate often display larger water demand and lower workability than the corresponding concrete with glaciofluvial aggregate.

In this article some results from a Swedish research programme (MinBas) on the use of crushed fine aggregate in concrete are presented. The fine aggregates have been analysed thoroughly, both regarding their material properties, i.e., petrography, particle shape, grading and sand equivalent value, and their rheological behaviour in micromortar, mortar and concrete. This article presents results from the mortar tests and describes the influence of the physical

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properties of the fine aggregate on the rheological properties of the mortar phase of concrete. Results from the micromortar and concrete experiments are presented separately in [3,4].

2. Experiments

2.1. Materials

2.1.1. Cement

A Swedish cement (CEM II/A-L 42.5 R), was used throughout the investigation. The cement, with 13% co-ground limestone, was delivered by the Swedish cement producer Cementa AB. The specific surface area, according to the BET method, of the cement is approximately 1740 m^2/kg.

2.1.2. Artificial paste

Normal cement reacts, stiffens and hardens with time. Consequently, the rheology of cement based mortars change with time due to the cement hydration. In some experiments, paste was added successively to the mortar in order to evaluate the effect of a change in paste volume. Fore these experiments an artificial paste was developed and used as a substitute of the cement paste. The artificial paste consisted of a blend of dispersed silica fume, fine quartz and water. The silica used is marketed by Elkem ASA Materials under the brand name Elkem Microsilica® 940U. The fine quartz is marketed by Sibelco under the brand name SIKRON® M300. Both the silica fume and quartz can be considered as inert and chemically stable at the chemical conditions of the experiments, i.e., dispersed in deionised water with an initial pH of approximately 6.5. The rheology of the paste was measured with a viscometer to verify that it displayed similar behaviour as ordinary Portland cement pastes with w/c-ratio of 0.57, i.e., Bingham behaviour. The paste viscometer and the used shear sequences have previously been described in [3].

2.1.3. Fine aggregates

A total of 14 fine aggregates (0–2 mm) were used in this work. Thirteen of them originates from crushed granitoid rocks (C1–C13) and one is a natural fine aggregate (N1), mainly of granitoid origin. The crushed fine aggregates were taken out from quarries located in different regions of the old Svecofennian shield in Sweden and are, thus, expected to give a good representation of the spread in properties found in Swedish crushed fine aggregates. Fine aggregate N1 is commercially available for concrete production and was used as the reference fine aggregate. It is typical of the sort used for concrete production in Sweden. The aggregates have been characterized thoroughly regarding their physical properties. The shape of the aggregates, which is described with an *f*-value, i.e., *f*-aspect, *f*-shape, *f*-radio and *f*-circle (Fig. 1), has been measured through image analysis of epoxy-baked thin section samples in optical microscopy. Both cut and lying particles have been analysed and the results show that in the cut samples the shape is mainly coming from flakiness [5]. Depending of the measured *f*-values, the particles are divided into four different shape categories, i.e., very elongated, elongated, cubic and circular. The *f*-values corresponding to the different shapes categories are specified below:

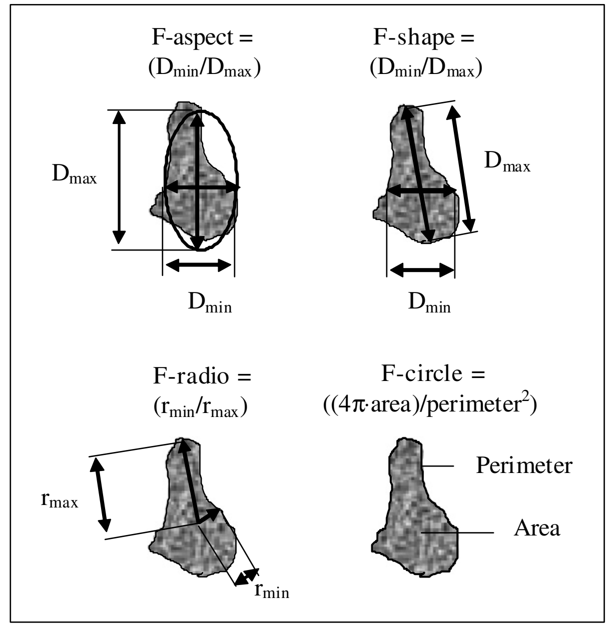

Fig. 1. Definitions of the different *f*-parameters describing the roundness of the particles.

$0 \leqslant f\text{-value} < 0.25$: very elongated,
$0.25 \leqslant f\text{-value} < 0.50$: elongated,
$0.50 \leqslant f\text{-value} < 0.75$: cubic,
$0.75 \leqslant f\text{-value} \leqslant 1$: circular.

The specific surface area and the particle size distribution of the fines, i.e., particles smaller than 0.25 mm, were also measured. The specific surface area was measured through nitrogen adsorption using BET theory while the particle size distribution was measured with an instrument based on light scattering/ diffraction (Malvern mastersizer). Both these analyses were conducted at Cementa Research AB in Slite, Sweden.

In addition to the mentioned analyses the fine aggregates were also analysed with the sand equivalent test (SE-test). The test was done in accordance with the European standard EN 933-8.

Further details on the properties of the fine aggregate and the methodology are given in the research reports [5,6].

In Table 1, the SE-value, specific surface area and the different *f*-values are presented. The presented *f*-values are mean values of the *f*-value of the different size fractions of the fine aggregates. Table 2 shows *f*-values for several fractions of a few fine aggregates that are studied more in detail in the section on standardized grading curves below.

From Table 1, it can be concluded that fine aggregate N1 has the most rounded particles, which was expected

Table 1
Sand equivalent value, specific surface area, *f*-aspect, *f*-shape, *f*-radio and *f*-circle of the fine aggregates

Fine aggregate	Sand equivalent (%)	Specific surface area (m^2/kg)	*f*-Aspect	*f*-Shape	*f*-Radio	*f*-Circle
N1	75	2650	0.59	0.53	0.40	0.64
C1	69	610	0.49	0.45	0.34	0.65
C2	57	1150	0.44	0.40	0.30	0.59
C3	56	976	0.41	0.37	0.28	0.59
C4	76	520	0.53	0.47	0.34	0.61
C5	68	2800	0.46	0.41	0.31	0.62
C6	68	890	0.44	0.41	0.31	0.63
C7	64	2490	0.47	0.42	0.28	0.55
C8	89	780	0.41	0.37	0.28	0.57
C9	41	4140	0.49	0.45	0.35	0.69
C10	82	840	0.48	0.42	0.32	0.60
C11	80	870	0.44	0.39	0.28	0.55
C12	74	1030	0.43	0.38	0.28	0.58
C13	76	920	0.45	0.40	0.30	0.59

The specific surface area was measured on the 0–0.25 mm fraction of the fine aggregates. The *f*-values are average values of measurements on individual fractions in the interval 0.075–1.0 mm.

Table 2
Particle shape of different fractions of a few fine aggregates expressed as *f*-aspect, *f*-shape, *f*-ratio and *f*-circle

Fine aggregate	*f*-Aspect				*f*-Shape			
	0.075–0.125	0.125–0.25	0.25–0.50	0.50–1.0	0.075–0.125	0.125–0.25	0.25–0.50	0.50–1.0
N1	0.58	0.59	0.58	0.59	0.54	0.48	0.54	0.54
C1	0.47	0.48	0.50	0.52	0.44	0.43	0.45	0.46
C2	0.42	0.44	0.45	0.44	0.39	0.39	0.41	0.39
C3	0.39	0.35	0.44	0.47	0.35	0.33	0.38	0.42
C4	0.52	0.50	0.54	0.54	0.47	–	0.45	0.50
C8	0.40	0.42	0.37	0.44	0.37	0.38	0.35	0.38
	f-Radio				*f*-Circle			
N1	0.45	0.33	0.41	0.42	0.77	0.45	0.63	0.70
C1	0.34	0.33	0.35	0.34	0.69	0.60	0.68	0.61
C2	0.30	0.30	0.30	0.29	0.62	0.54	0.63	0.57
C3	0.27	0.24	0.30	0.32	0.60	0.56	0.57	0.63
C4	0.37	0.28	0.31	0.38	0.71	0.53	0.55	0.65
C8	0.28	0.28	0.26	0.28	0.62	0.54	0.58	0.55

since water sorting and weathering gives particles with more rounded shape and smoother surfaces than crushed aggregates. Furthermore, the fines, <0.25 mm, from fine aggregate N1 display a relatively large specific surface area; only two of the fines from the crushed fine aggregates displayed a larger (C5 and C9) area. The large specific surface area of the fines from N1 is probably due to presence of extremely fine-grained weathering clays. Fines C9 is largely seriticized, which may explain the large specific surface area. Sericite is a badly ordered muscovite in clay size.

The grading curves of the fine aggregates in this investigation are shown in Fig. 2. From the figure it can be concluded that the crushed fine aggregates contain significantly larger amounts of fines, up to more than twice as much, than the reference fine aggregate N1. However, within the

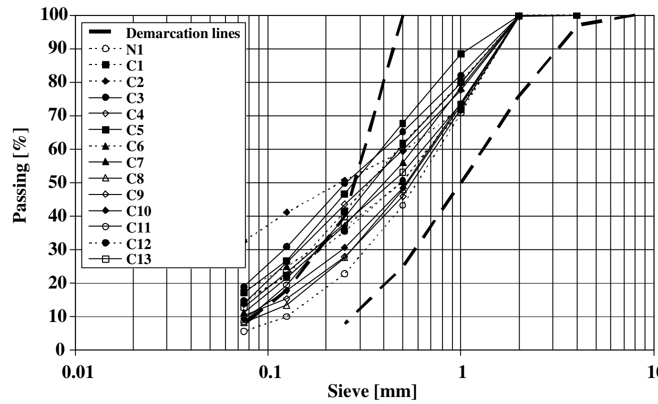

Fig. 2. Grading curves of the fine aggregates.

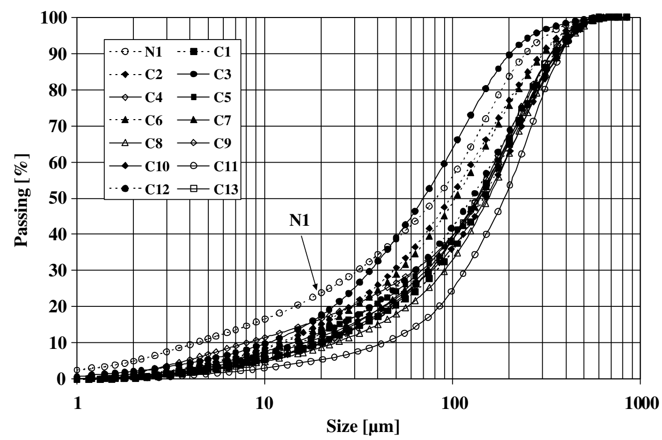

Fig. 3. Particle size distribution of fine aggregate fines passing 0.25 mm.

fines fraction (<0.25 mm) the fines from N1 appear to be more fine-grained than the other fines, i.e., fines C1–C13 (Fig. 3). The amount of particles smaller than 10 μm in the fines fraction of N1 was 16.5% compared with the crushed fine aggregates which varied between 3% and 11.5%. This can be due to presence of extremely fine-grained weathering clays in the natural fine aggregate (N1). However, since the crushed fine aggregate contains significantly larger amounts of fines, <0.25 mm, the difference in the number of particles smaller than 10 μm will be balanced.

2.1.4. Superplasticizer

The superplasticizer used in this investigation was Glenium 51 from Master Builders. Glenium 51 is based on a modified polycarboxylate ether type of polymer and the dry content is approximately 35%.

2.2. Characterization of mortars

2.2.1. Mix design

The mortars were designed to represent the mortar phase of a hypothetical concrete with a given mix design. In this work we chose to work at a constant water to

Table 3
Mix design of the mortars

Constituents	Amounts (g/l)
Cement	635
Fine aggregate, 0–2 mm	1148
Water	362
w/c-ratio	0.57
Superplasticizer[a]	0–4.5

[a] With a dry content of 35% by weight.

cement ratio and constant cement content. The mix design of the mortars is described in Table 3.

Furthermore, in one series of experiments we worked with mortars containing an inert artificial paste. The paste volume of these mortars was successively increased, i.e., in three steps from a paste volume of 57% to 68%, by adding more of the artificial paste. Thus, the mortars can be considered to represent mortars which contain different amounts of cement at a given w/c-ratio. The artificial paste was used to avoid any time dependence effects due to cement hydration during the experimental time. The composition of the initial mortar and the paste added are shown in Table 4.

The mortars and the artificial paste were mixed for four minutes in a Hobart mixer equipped with a paddle stirrer (Fig. 4). 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 4
Mix design of mortars with the artificial paste and the paste used to adjust the paste volume of the mortars

Constituents	Mortar (g/l)	Artificial paste (g/l)
Quartz	565	998
Silica fume	70.6	124.6
Fine aggregate, 0–2 mm	1149.8	–
Water	317.8	561.5
w/p-Ratio[a]	0.50	0.50

[a] Water/powder-ratio.

Fig. 4. Hobart mixer equipped with a paddle stirrer.

2.2.2. Rheological measurements

The rheological properties of the mortars were studied with a rotational viscometer (Contec 4) suited for measurement on coarse particle suspensions (Fig. 5). The measuring system consists of concentric cylinders of which the outer cylinder can be rotated and the inner cylinder is stationary. The inner cylinder is ribbed while the outer cylinder is lined with a wavy rubber. The radius of the inner and outer cylinder is 65 mm and 85 mm, respectively, thus providing a gap of 20 mm.

During measurement, the sample is sheared in the gap between the cylinders by the rotational motion of the outer cylinder. The outer cylinder is rotated according to a predefined velocity profile which is described by an up and down curve where the speed is first increased stepwise from zero to 0.45 rps and then lowered again (Fig. 6). The velocity profile also includes a measuring point, segregation

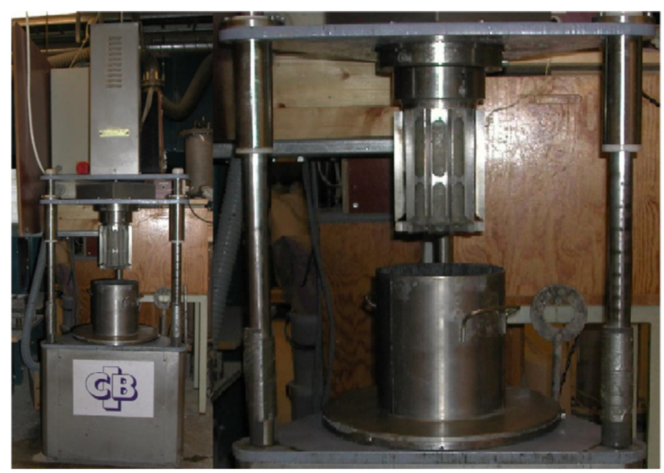

Fig. 5. Viscometer, Contec 4, with concentric cylinders used for characterization of mortars.

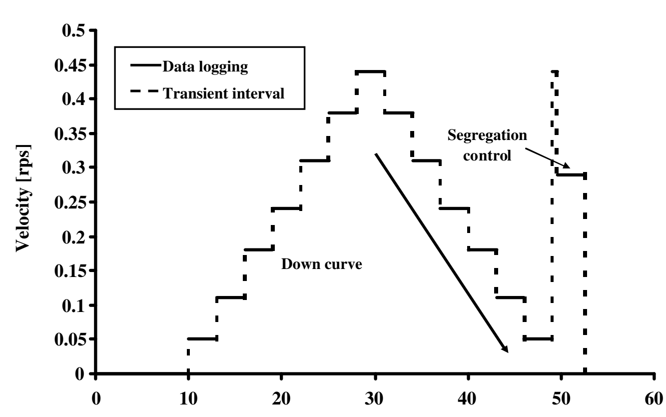

Fig. 6. Measuring sequence used to characterize the mortars.

control, which can be used to verify that the sample has remained its homogeneity during the measurement. The homogeneity is verified by calculating the relative change in slope (viscosity) between the points in the down curve and the segregations point. Values below 5% indicate that no significant segregation has occurred during the measurement [7]. The segregation control values of the studied mortars in this article were all $\leqslant$5%.

During the measurement the generated torque is continuously registered by the inner cylinder. The torque and speed of rotation are recalculated to shear stress (τ) and rate of shear ($\dot{\gamma}$), respectively. By applying the Bingham model (Eq. (1)) to the registered data at the down curve, the rheological parameters yield stress (τ_0) and plastic viscosity (μ_{pl}) are obtained. The calculation is done with the software FreshWin 4.0:

$$\tau = \tau_0 + \mu_{pl} \cdot \dot{\gamma} \tag{1}$$

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 described 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 concretes resistance towards flow. It can be considered as the internal friction of the concrete. The slump value which is a one point test gives an indication on the yield stress, but cannot be used to asses the plastic viscosity. By the use of the viscometer both these parameters can be obtained in a single measurement.

3. Results and discussion

3.1. Mortar rheology

The rheological properties of mortars containing different types of fine aggregates, i.e., fine aggregates from crushed bedrock, have been evaluated with a viscometer suited for coarse particle suspensions. The fine aggregates displayed different grading curves, particles shapes, specific surface area of the fines fraction and SE-values. The mortars were analysed both with and without addition of a superplasticizer and at different paste volumes by utilising an artificial paste. In one set of experiment the grading curve of a few selected fine aggregates were standardized, i.e., made similar, in order to study the influence of the particle shape. Furthermore, the amount of fines was varied in order to study their influence on the rheology of the mortar.

3.1.1. Influence of different fine aggregates

The results clearly show that the properties of the fine aggregate strongly influence the yield stress and plastic viscosity of the mortars (Fig. 7). These results are consistent with the results found in the concrete tests within the research programme, where the slump value of the concretes varied between 5 mm and 200 mm depending on

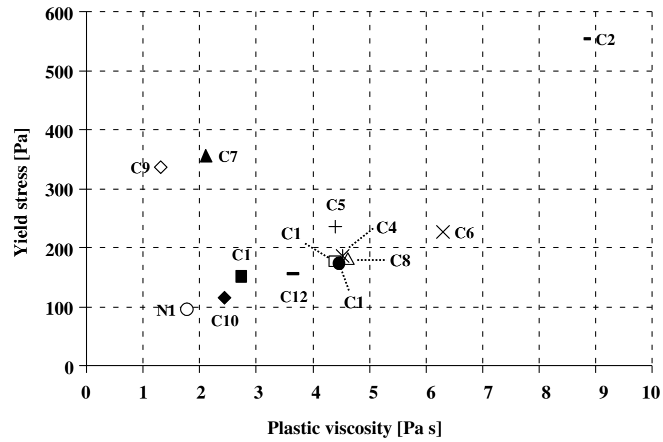

Fig. 7. Yield stress versus plastic viscosity of mortars containing fine aggregates with their original grading curves.

the used fine aggregate [4]. In the mortar tests the yield stress and plastic viscosity varied in the range between 96 Pa and 550 Pa and 1.3 Pa s and 8.8 Pa s, respectively. It can also be concluded that the mortars with fine aggregate from crushed bedrock generally display both higher yield stress and plastic viscosity than the reference mortar with the natural fine aggregate (N1). This is a result of both the higher amount of fines and the more irregular particle shape shown by the crushed fine aggregate. The strong influence of the fine aggregate properties on mortar rheology has also been shown in [8] where the water demand varied over a twofold range depending on the properties of the fine aggregate. The variation in water demand was primarily related to the variations in the surface area of the fines fraction. According to the same author [9] an increase in fineness of the fine aggregate (sand) mainly results in an increased yield stress, while an increased fine aggregate content results in both a higher yield stress and plastic viscosity of the mortar.

However, since the fine aggregates used in this investigation displayed large variations in the amount of fines, specific surface area and particle shape it is difficult to find clear correlations between these parameters and the rheological properties of the mortar. Regarding the SE-value, it was not possible to find any correlation between the rheological parameters and SE-values above 75%. But for lower SE-values, i.e., $\leqslant$75%, a significant increase in the yield stresses and, thus, water demand could be observed with decreasing SE-values. In Saudi Arabia the SE-value must be $\geqslant$75% in order to fulfil the regulations for fine aggregate used in concrete for bridges and road constructions [10].

The relationship between the SE-values and the plastic viscosity was more unclear. However, all the crushed fine aggregates contained relatively large amounts of fines and consequently have a larger surface area which needs to be wet in order for the mortar to be workable. The large amounts of badly shaped fines are believed to be the major reason for the higher water demand of the mortars with crushed fine aggregates, i.e., higher yield stress and plastic viscosity.

This is clearly true for fine aggregate C2 which suffers from very high amounts of fines, especially in size fractions smaller than 0.125 mm (see Fig. 2). The mortar containing fine aggregate C3 was too stiff to be measured in the viscometer. This fine aggregate also contains high amounts of fines and petrography analysis shows that it contains high amounts of the flaky mineral biotite [5], especially in the fines fraction, which is known to have a negative effect on the workability of concrete [11–13]. The results from this work indicate that the particle shape mainly influence the plastic viscosity of the mortar. However, results from other research indicate that the shape also influence the yield stress [14].

The mortars with fine aggregate C7 and C9 displayed a high yield stress and a relatively low plastic viscosity. This differs from the general pattern in Fig. 7 where a high yield stress is accompanied by a high plastic viscosity. Consequently, this means that these mortars display a high initial resistance to motion, but well in motion they flows more easily than a mortar with corresponding yield stress but a higher plastic viscosity.

3.1.2. Influence of particle shape

In order to evaluate the influence of particle shape on the rheological properties of mortars the grading curves of a few fine aggregates were standardized. This was done by combining different fractions of the fine aggregates to a grading curve similar to the one for fine aggregate N1 (see Fig. 2). The rheological parameters yield stress and plastic viscosity of mortars containing the fine aggregates with standardized grading curves are shown in Fig. 8.

The results show that the major difference between the mortars with glaciofluvial fine aggregate (N1) and the crushed fine aggregate can be seen in the plastic viscosity. The difference can be considered to be a particle shape effect, i.e., the higher viscosity of the mortars with crushed fine aggregate is a result of increased particle interference

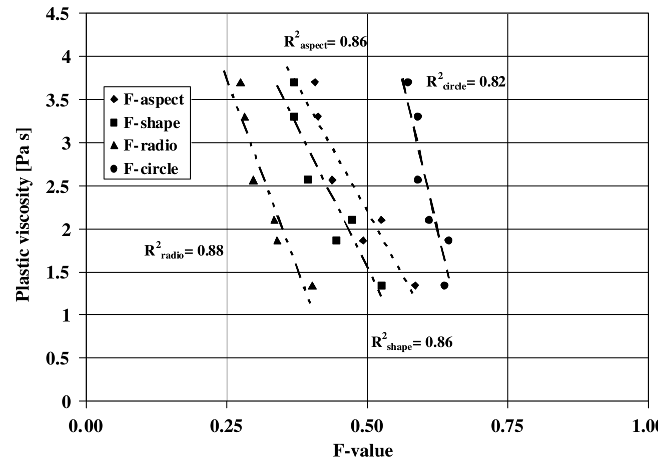

Fig. 9. Plastic viscosity versus the different *f*-values.

between non-spherical particles. It is well known that any deviation from a spherical particle shape results in an increase in viscosity if the measurement is done at the same phase volume [15]. A correlation analysis between the plastic viscosity and the different *f*-values in Table 1 gives a correlation coefficient between 0.82 and 0.88 (Fig. 9). A change in *f*-aspect from 0.59 to 0.41, thus a change from a cubic to elongated shape, resulted in almost a threefold increase, i.e., 2.7 times, of the plastic viscosity. However, how these differences in plastic viscosity of the mortar affect the workability and rheology of concrete is a subject of further research.

The corresponding correlation coefficient values for the yield stress are 0.09 and 0.31 (Fig. 10), i.e., the shape of the aggregate seems to have a limited influence on the yield stress. The results also show that the major reason for the high yield stress and plastic viscosity of the mortar with fine aggregate C2 shown in Fig. 7 is the large amounts of fines. As mentioned above it was impossible to analyse the mortar with fine aggregate C3 (original grading), but when the grading curve was standardized it displayed similar yield stress as the mortar with aggregate N1. However,

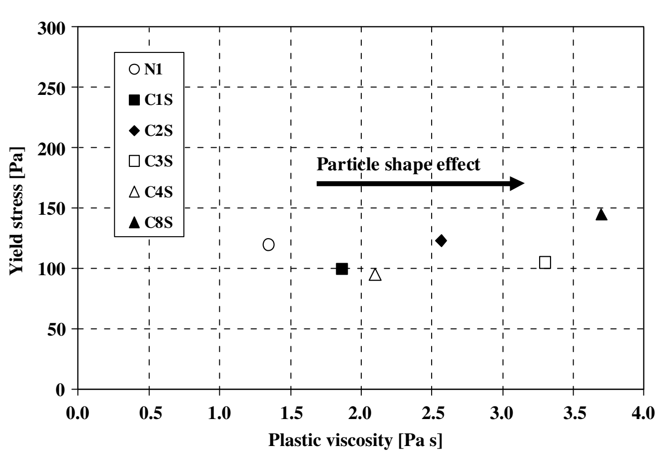

Fig. 8. Yield stress versus plastic viscosity of mortars containing fine aggregates with standardized sieve curves.

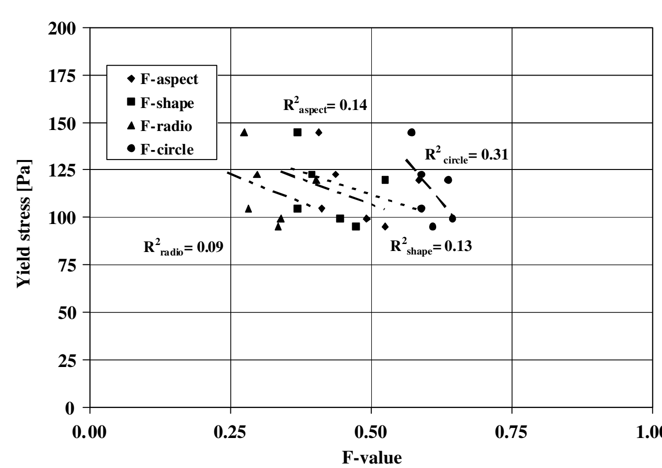

Fig. 10. Yield stress versus the different *f*-values.

the plastic viscosity was more than twice as high due to particle shape effects.

3.1.3. Influence of fines content

Moderate amounts of fines generally have a positive effect on the properties of concrete, i.e., consistency and workability [16]. Increasing amounts of fines increase the required amount of water to wet the particle surfaces adequately and to maintain a specified workability [17].

The effect of the fines content on the rheological properties of mortars is shown in Figs. 11 and 12. In Fig. 11, it can be seen that the yield stress of the mortars starts to increase linearly at fines contents above 16%. Consequently, above this fines content the water demand of the mortars increases due to the change in the total surface area of the fine aggregates.

The effect of the fines content on the plastic viscosity of the mortars appears to be more complicated than the effect on the yield stress. For the mortar with fine aggregate N1 virtually no effect could be observed within the studied range of fines content (Fig. 11). For the mortars with crushed fine aggregates the results indicate that the plastic viscosity pass through a minimum at a certain fines content, which seems to differ with the type of fine aggregate.

Similar effects have been observed for concrete, where the fines content at which the viscosity passes through the minimum has been found to depend on both the w/c ratio and the aggregate to cement ratio (a/c ratio) [18]. This suggests that the effect found in the mortars would be more pronounced at a higher a/c ratio.

However, the phenomenon could be explained in terms of particle friction. At the lowest fines content there is not enough fines to fill out the voids between the larger aggregate particles which results in a high internal friction and thus a high viscosity. As the fines content increases the friction between the larger aggregate particles decreases and consequently, the viscosity is reduced. When the fines content increase even further the plastic viscosity may increase due to the increase in the total surface area of the fine aggregates. The magnitude of the increase might also depend on the particle shape of the fines. The fines (C3) which resulted in the most significant increase in plastic viscosity displayed the lowest *f*-aspect value and also contain the highest amount of biotite.

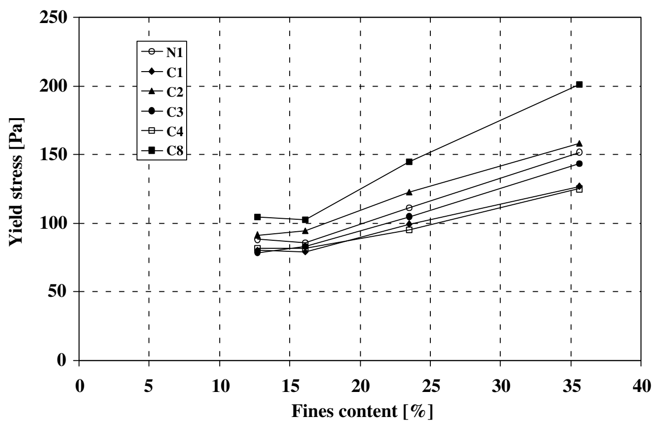

Fig. 11. Yield stresses of the mortars as a function of the fines content of the fine aggregate.

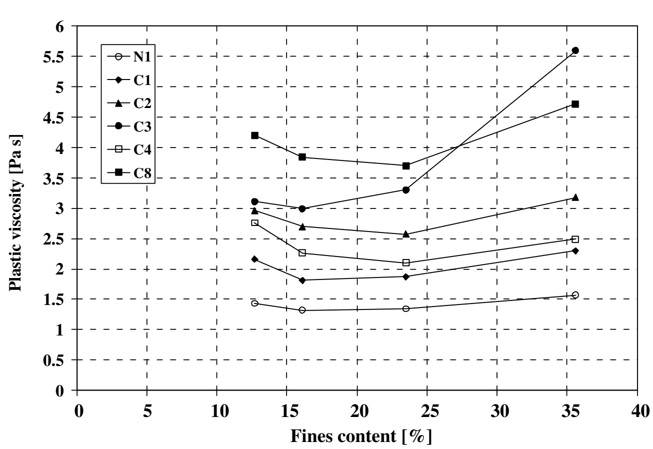

Fig. 12. Plastic viscosities of mortars as a function of the fines content of the fine aggregate.

3.1.4. Influence of superplasticizer

The results in Fig. 7 showed that the "water demand", expressed by the rheological parameters, of the mortar with crushed aggregate was slightly higher and in some cases much higher than the corresponding mortar with aggregate N1. By using an effective superplasticizer it is possible to reduce the yield stress and plastic viscosity of the mortars (Figs. 13 and 14). However, the required dosage of superplasticizer to reach a certain yield stress differs depending on the initial yield stress and also on the properties of the aggregate. The required dosage to reach a yield stress value of 30 Pa of the studied mortars in Fig. 13 varied approximately between 0.07% and 0.25% of the cement content.

3.1.5. Influence of paste volume

Concrete with crushed aggregate often requires slightly higher cement content in order to reach the same workability as a concrete with glaciofluvial aggregate. The effect of

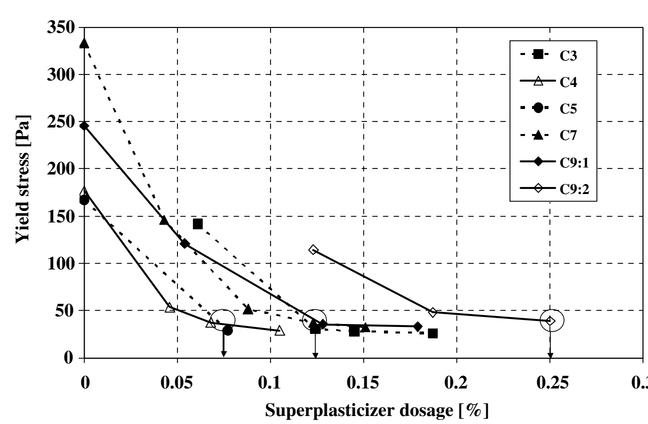

Fig. 13. Yield stress versus dosage of superplasticizer.

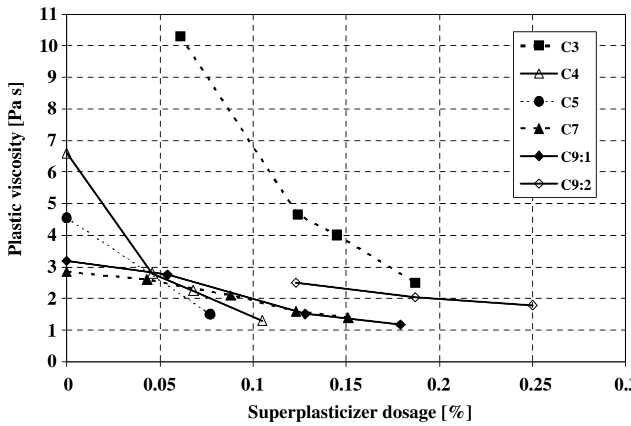

Fig. 14. Plastic viscosity versus dosage of superplasticizer.

increased cement content at constant w/c-ratio on the rheological properties of mortars is shown in Figs. 15 and 16. In these experiments an artificial paste was used instead of a real cement paste in order to simulate the effect of increased cement content. The results show that the importance of the fine aggregate characteristics, i.e., the shape, specific surface area and grading curve, becomes less

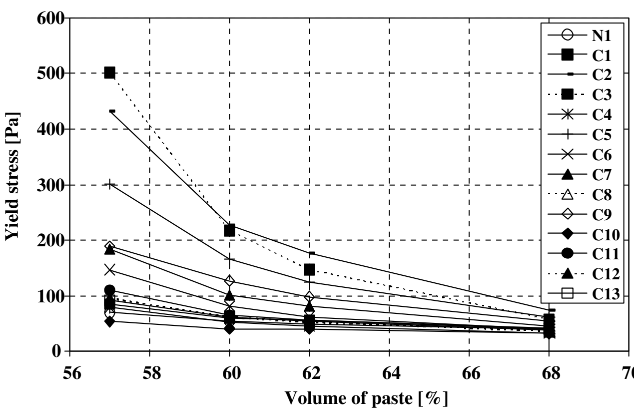

Fig. 15. Yield stress versus volume of artificial paste.

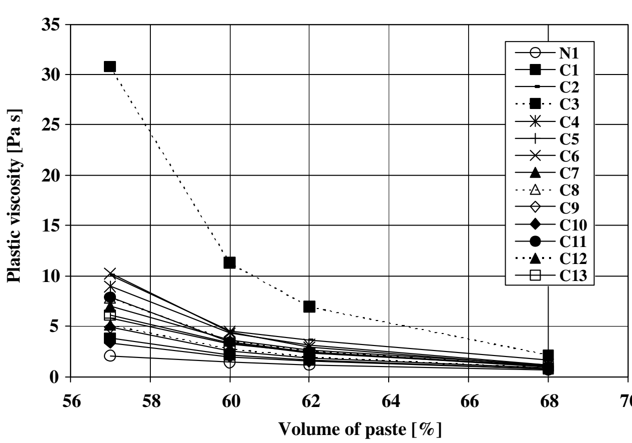

Fig. 16. Plastic viscosity versus volume of artificial paste.

important with increasing paste volume. This is a consequence of reduced particle interference with the increased interparticle distance and the simultaneous reduction of the aggregate volume. Similar results have been reported for micromortar and concrete [3,4,11,19]. The results also show that for some of the mortars, a slight increase of the paste volume is sufficient to bring down the yield stress to the same level as the initial value of the mortar with fine aggregate N1, while others require a higher paste volume than 62%. The required increase in paste volume in order to bring down the plastic viscosity seems to be slightly larger.

4. Conclusions

In this paper, results from a study of the influence of crushed fine aggregates on the rheological properties of the mortar phase of concrete have been presented. The results show that the rheological properties and water demand of mortars are strongly dependent on the properties of the fine aggregate. The higher yield stress of the mortars with crushed fine aggregate is believed to mainly originate from the relatively high amounts of fines often found in crushed fine aggregate. This was clear for the mortars with fine aggregate C2 and C3 which displayed very high yield stresses. The high amount of fines also contributes to the plastic viscosity by increasing the interparticle friction. However, the results also show that the higher viscosity of the mortars with crushed fine aggregates is a particle shape effect. A change in the *f*-aspect value from 0.59 to 0.41 resulted in almost a three folded increase of the plastic viscosity.

The results also show that the effects of poorly graded and shaped fine aggregates can be eliminated or reduced by increasing the paste volume of the mortars. This is consistent with the results from concrete tests and can partly be considered to be a result of decreased interparticle interference with increased paste volume.

Furthermore, the high yield stress and the plastic viscosity resulting from the high amounts of fines can effectively be reduced by the use of an effective superplasticizer.

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