RHEOLOGY OF SELF-COMPACTING MORTARS
Influence of particle grading

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ABSTRACT

The influence of different sands on the rheological parameters of self-compacting mortars has been investigated. Tests have been carried out on mortars with sands having five different grading curves. The fineness modulus varied between 1.5 and 3. Eight different mortar mixes with water/cement ratios between 0.32 and 0.42 have been used. The binder was a mixture between 86% CEM II A-L 52.5 cement with 14 percent limestone filler, and 14% flyash.

The results indicate that the particle size distribution and the particle shape influence the yield stress and the viscosity. Increasing fineness as well as increasing aspect leads to increase in yield strength and viscosity. Such information can be used for tailoring mortars for special purposes.

There are indications that the new generation superplastizisers increase the relaxation period needed to obtain equilibrium flow of mortar or concrete compared to traditional admixtures. This should be taken into account in the selection of measuring procedures.

Key words: rheology, self-compacting, mortar, sand, particle size distribution, particle shape

1. INTRODUCTION

Self-compacting concrete (SCC) was developed in Japan in 1988 [1]. This type of concrete has a great potential. Traditional concrete needs to be vibrated to ensure proper compaction. Vibration takes time and often creates defects in the hardened concrete. Furthermore, vibration is noisy and gives workers health problems. Thus, it is of great interest to control the technological aspects with relevance to the application of SCC, e.g. to establish a basis for the optimisation of concrete composition with regard to flow and homogeneity. For this purpose, models for the effect of paste composition (binder type, chemical admixtures, and mineral additions), air content, and aggregate type and grading on the rheological properties of concrete need to be developed.

This paper addresses the influence of particle shape and grading curve for the sand fraction in the mortar on the rheological parameters. The paper is based on some of the experimental results from the master thesis by Rune M. Jensen [2], studying the influence of different cement- and filler types as well as different sands on the rheological behaviour of self-compacting paste, mortar and concrete.

2 MATERIALS

2.1 Cement, fly ash and additives

All the experiments reported in this paper have been carried out with the same constituents of the binder:

- CEM II/A-L 52.5. The Danish "**BASIS**® cement" containing 14% limestone filler. Dry density: 3100 kg/m^3, eigenpacking: 61%.
- Fly ash according to the EN 450 standard. Dry density: 2200 kg/m^3, eigenpacking: 68%.
- Viscocrete-3 from SIKA as the superplasticizing agent. Density: 1010 kg/m^3, solid content: 30 %.

Table 1: Grading of cement and flyash measured with laser particle analyser

	0.3 µm	0.5 µm	0.7 µm	1 µm	2 µm	3 µm	5 µm	7 µm	10 µm	12 µm	15 µm	20 µm	30 µm	50 µm	70	100 µm
Cement	2.6	6.1	8.6	11.9	21.8	30.3	41.3	48.8	57.8	63.0	70.3	81.8	96.3	100	100	100
Flyash	0.8	1.9	2.7	3.9	8.3	13.2	21.1	27.4	35.3	39.9	46.2	55.1	68.0	87.9	98.0	100

2.2 Sand

Ten different sands have been used in the experimental program; five natural and five artificial, each pair having identical grading curves but different particle shape and surface texture as seen in figure 2.

The five artificial sands are made from quarts sand of high purity from a deposit close to Silkeborg in Denmark. After sieving of the material, sands with five different grading curves have been produced. It is assumed that the particle shape and the mineralogy of these five types of sand are identical. The grading curves of the artificial sands are as close to the natural types as practical possible.

Data on the ten different sands are presented in table 2.

Table 2: Data on the sands used for the mortar tests

			Grading 1		Grading 2		Grading 3		Grading 4		Grading 5	
			Nat. 1	Art. 1	Nat. 2	Art. 2	Nat. 3	Art. 3	Nat. 4	Art. 4	Nat. 5	Art. 5
Sieve size	4	mm	100	100	100	100	99	100	99	100	99	100
	2	mm	99	99	97	97	81	84	79	80	84	85
	1	mm	95	95	86	88	67	68	59	62	52	53
	0.5	mm	79	80	53	55	52	56	35	37	15	14
	0.25	mm	29	37	17	14	28	34	16	19	3	4
	0.125	mm	3	3	5	1	7	9	6	8	0	0
	0.075	mm	1	1	1	0	3	3	2	2	0	0
Density, ssd		kg/m^3	2613	2627	2632	2640	2645	2623	2615	2653	2625	2631
Density, dry		kg/m^3	2591	2625	2618	2635	2633	2608	2579	2628	2613	2622
Absorption		%	0.82	0.08	0.52	0.20	0.54	0.54	1.42	0.26	0.48	0.27
Bulk density		kg/m^3	1677	1612	1818	1668	1890	1835	1818	1851	1795	1719
Eigenpacking		%	65	61	69	63	69	70	70	70	69	66
Fineness modulus1)		-	1.47	1.38	1.95	1.96	2.20	1.96	2.59	2.48	2.97	2.94
Mean size		mm		0.35		0.5		0.5		0.7		1.0
Shape1)			R	R	R	R	A	R	A/R	R	A	R
Surface 2)			R	S	S	S	R	S	R	S	R	S

1): According to [3]
2): R: Rounded; A: Angular
3): S: Smooth; R: Rough

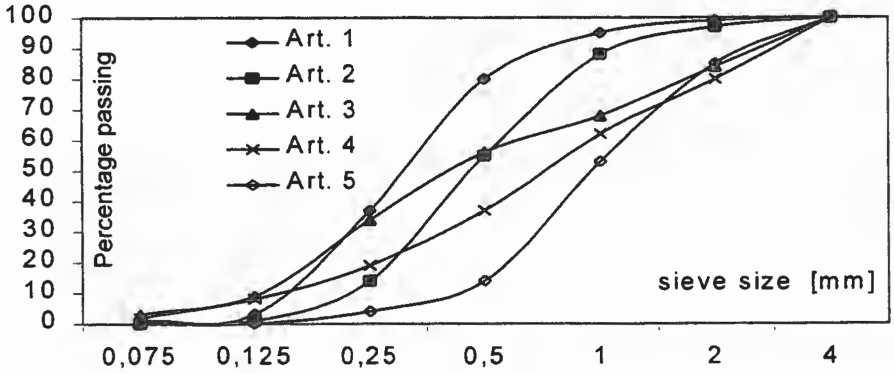

Figure 1 *Grading of the artificial sands*

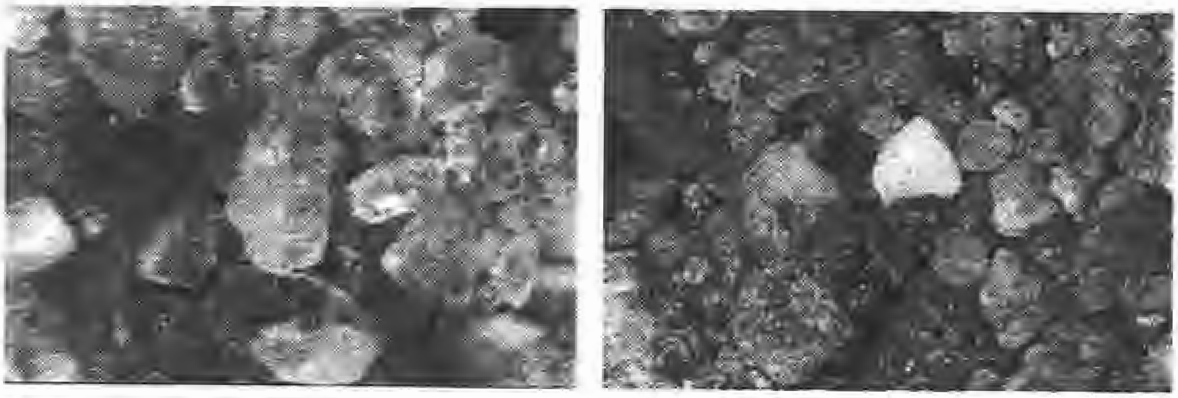

Figure 2: *Photographs of artificial sand (left) and natural sand (right) of grading 4. magnification app. 4 times*

2.3 Mortar mixes

The relative volumes of cement, flyash, additives and sand were kept nearly constant. The main parameter varied was the amount of water, varying from 200 kg/m^3 to 244 kg/m^3, ref. table 3. The mixes equal the mortar in concrete with d_{max} = 16 mm and a powder content at 430 kg/m^3, which is quite common for self-compacting concrete. An overview of the number of tests is given in table 4.

Table 3: Mortar mix designs

Mix type	Unit	A	B	C	D	E	F	G	H
Cement	kg/m^3	617	612	607	602	597	592	587	583
Fly ash	kg/m^3	100	99.2	98.3	97.5	96.8	96	95.2	94.5
Water	kg/m^3	200	207	213	220	226	232	238	244
Viscocrete	kg/m^3	7.5	7.4	7.4	7.3	7.3	7.2	7.1	7.1
Sand*	kg/m^3	1371	1360	1349	1338	1327	1316	1306	1295
Paste vol.	l/m^3	468	473	477	481	486	490	494	498
w/c	-	0.32	0.34	0.35	0.37	0.38	0.39	0.41	0.42
w/p	-	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.37
Solid fraction	-	0.78	0.77	0.76	0.76	0.75	0.75	0.74	0.73

*: The weight depends on the actual density of the sand.

Table 4: Overview of mortar tests with varying mix composition (A-H), and grading (1-5) and type (natural or artificial) of sand.

Mix	Grading 1		Grading 2		Grading 3		Grading 4		Grading 5	
	Nat. 1	Art. 1	Nat. 2	Art. 2	Nat. 3	Art. 3	Nat. 4	Art. 4	Nat. 5	Art. 5
A										X
B								X		X
C		X		X		X		X	X	X
D		X		X		X	X	X		
E		X		X	X	X				
F		X	X	X						
G		X								
H	X	X								

The individual mortar mixes are named "sand-mix"; i.e. ART2D is a mortar containing artificial sand 2 and mix D.

3 EXPERIMENTAL

3.1 BML-viscometer

The BML viscometer [4] is a coaxial cylinder viscometer, where the control and data handling program normally measures the rheological parameters according to a Bingham behaviour, i.e.

$$\text{Torque} = G + H*\text{speed}$$

Where G is the force necessary to start movement of the concrete, and H is a measure of the resistance of the concrete against an increased speed of movement.

The viscometer measures the torque [Nm] as function of the speed [rotations pr second, rps]. The Reiner-Rivlin equation may be used for converting these actual measurements to the Bingham parameters yield stress, τ_o [Pa], and plastic viscocity, μ [Pas], according to [5].

$$\Omega = \frac{T}{4\pi h\mu}\left(\frac{1}{r_i^2}-\frac{1}{r_0^2}\right)-\frac{\tau_0}{\mu}\cdot\ln\left(\frac{r_0}{r_i}\right)$$

where

Ω : Angular velocity of the outer cylinder [rad/s]
T : Torque measured at the inner cylinder [Nm]
h : Height of inner cylinder [m]
r_i : Radius of inner cylinder [m]
r_0 : Radius of outer cylinder [m]

Since mortars normally are expected to behave as Bingham materials and hence have a yield value, there is a risk for plug-formation between the inner and the outer cylinder if the rotational speed is below a certain limit. Thus, if the rotational speed is below this limiting plug speed, then the material between the inner and the outer cylinder will not behave as a Bingham material, and the data can not be used for calculation of the rheological parameters. This limiting plug speed, N_p, can be calculated according to the following equation [5]

$$N_p = \frac{\tau_0}{\mu}\left[\frac{1}{2}\left(\frac{r_0^2}{r_i^2}-1\right)-\ln\left(\frac{r_0}{r_i}\right)^2\right]\cdot\frac{1}{2\pi}$$

For the mortars tested, the test procedure was:

Max rotational speed	0.42 rps
Min rotational speed	0.07 rps
No. of T/Ω points	6
Transient interval	2 sec
Sampling interval	3 sec
No. of sampling points	50
Height of inner cylinder	0.119 m
Radius of inner cylinder, r_i	0.085 m
Radius of outer cylinder, r_0	0.100 m

The speed-torque relation in each velocity interval is calculated from the 10 lowest points. This test procedure is the one used for traditional mortars, even when using plastizicers and superplastizicers.

3.2 Experimental artefact

Basically four different rheological behaviours exist.

Newtonian	$\tau = \acute{y}\mu$
Bingham	$\tau = \tau_0 + \acute{y}\mu$
Shear thinning	$\tau = \tau_0 + a\acute{y}^b$; $b<1$
Shear thickening	$\tau = \tau_0 + a\acute{y}^b$; $b>1$

where

τ is the stress [Pa]
τ_0 is the yield stress [Pa]
$\acute{y}$ is the shear rate [s^{-1}]
μ is the plastic viscosity [Pas]
a and b are characteristic parameters describing the shear rate dependency of the material tested

In several investigations on self-compacting concrete, shear thickening behaviours have been seen. This is also the case in the actual experiments, as can be seen from figures 5, 6 and 7, presenting the measurements. In the actual experiments, the mortars appear to have shear thickening behaviour. Others, e.g. [6], have also reported such behaviour for self-compacting concrete.

However, materials having shear thickening rheological properties are very rare. Therefore, the measured behaviour is assumed to be an artefact from the experimental set-up. Figure 3 illustrates the assumed relation between the shear rate and the torque during testing. Some relaxation takes place as function of time, hence the measurements takes place during the last two seconds for each step. The figure illustrates that the apparent shear-thickening behaviour might be caused by a longer relaxation period for the highest shear rates, than the app. 5 seconds used in each interval. Hence the measured torque might be too high, and linear interpolation will lead to too low and maybe even negative values for the yield stress.

For the lowest shear rate another phenomenon is illustrated – a slight recovery within the measuring time. Hence, calculating the speed-torque relation from the lowest 10 points will lead to a too low value of the torque. This will also result in too low values of the yield stress. Since the apparent shear thickening behaviour was not expected, no attempt was made to save the raw data for later recalculation, taken into account the above mentioned phenomena.

We have chosen only to use data for rotational speed less than 0.21 rps for calculation of the rheological parameters. None of the measurements were carried out at shear rates below the limiting plug speed N_p. No attempt to take the recovery at the lowest shear rate into consideration has for practical reasons been made. Hence negative yield values are reported, regardless their physical meaninglessness. However, we expect, that the ranking of the yield stress for the different mortars is correct.

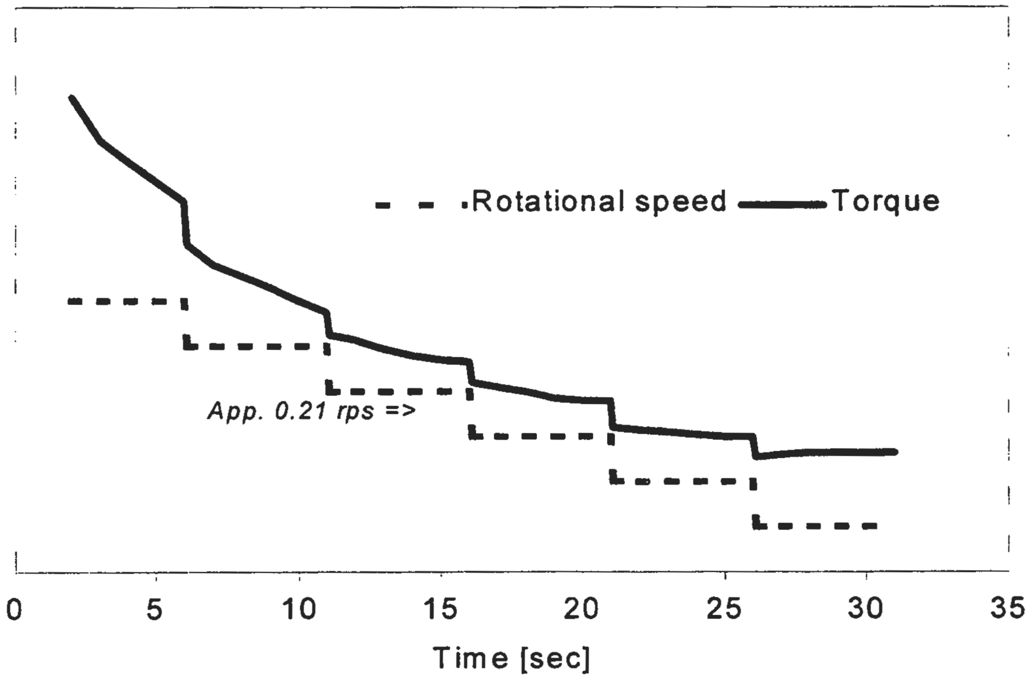

Figure 3: *Illustration of the assumed relation between shear rate and torque as a function of time.*

3.3 Mixing procedure

Mixing of the mortars was carried out on a 20-litre laboratory paddle-pan mixer (Hörz Getriebe) The batch size was 7 litres.

The following mixing schedule was used for all tests with the artificial sand.

- Aggregates and 2/3 of the water
- 60 sec mixing
- 10 min rest in order to achieve saturation of the aggregates
- Cement and flyash is added immediately before the final mixing.
- The remaining 1/3 of the water, including additives, are added during the first 15 sec of the final mixing period.
- 90 sec mixing

Since the natural sand has a higher absorption, the 10 min rest was not enough time to saturate these sands. Therefore the sand and 2/3 of the water was mixed 24 hours before final mixing. This is marked with "-w" in the legends in the following.

4 RESULTS

Figure 4 shows the repeatability of the BML-viscometer when using it for measurements on self-compacting mortars. Three different mortar mix compositions have been tested twice. The almost identical measurements indicate that it is reasonably to use single measurements.

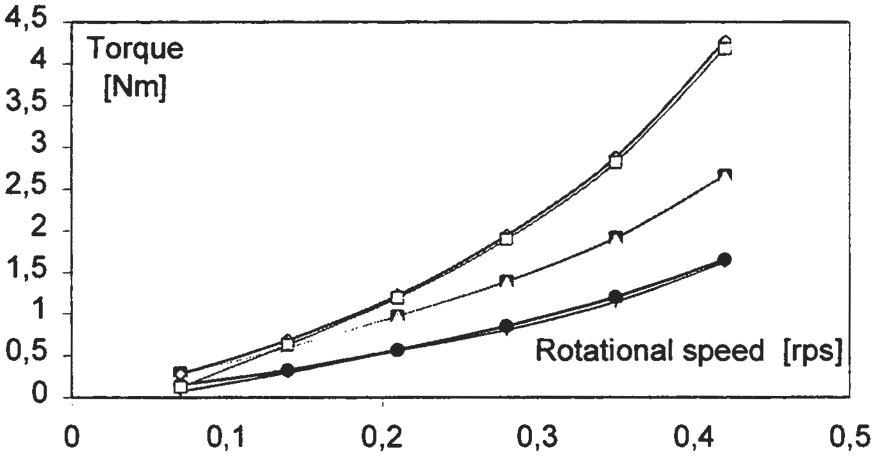

Figure 4: Repeatability of measurement on the BML-viscometer for three different mortar mixes. [2]

The following figures illustrate the influence of sand grading and mix design (water content) on the rheological behaviour of the mortars, figures 5 and 6.

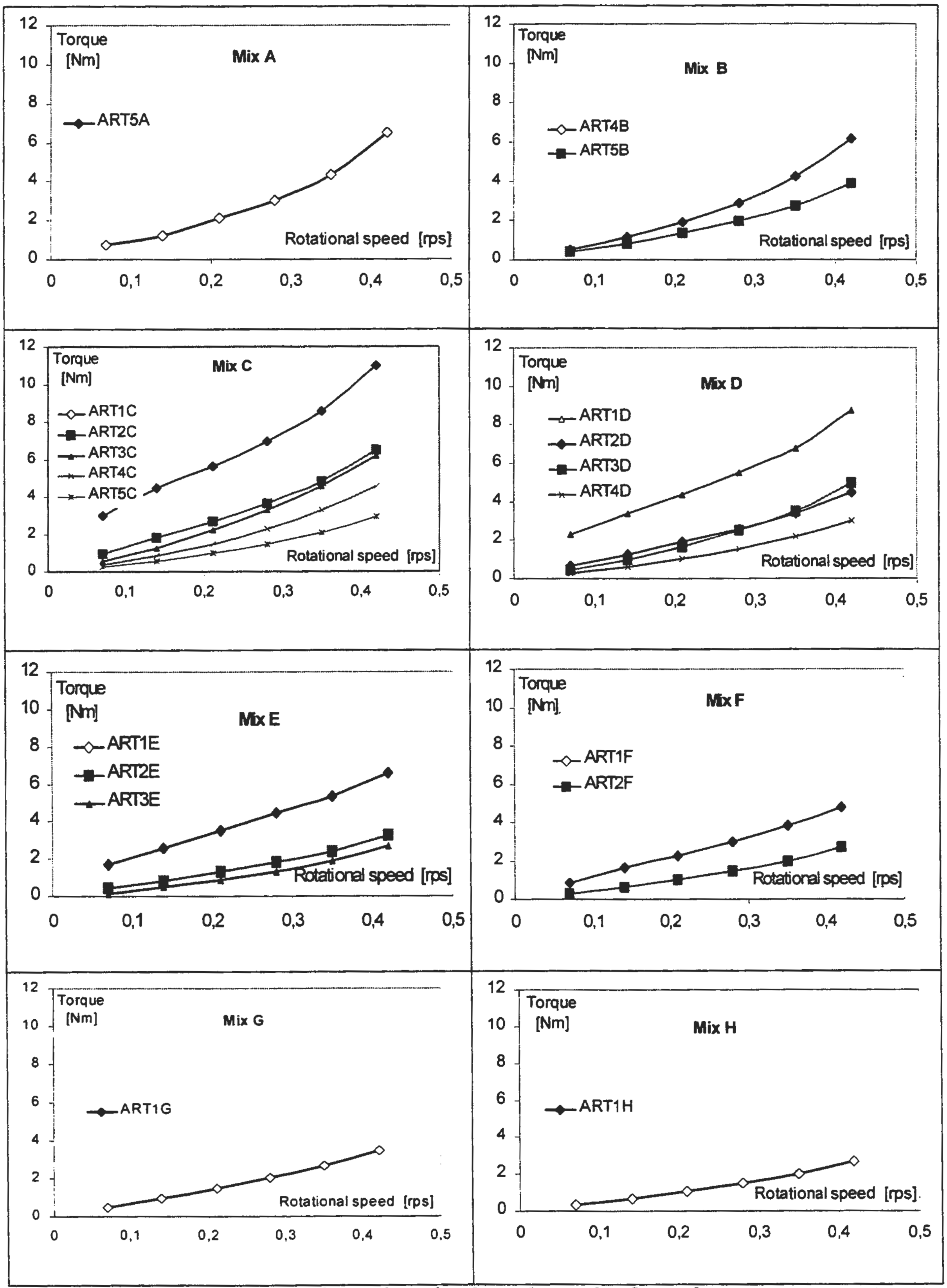

Figure 5: *Influence of grading of artificial sands on the flow of mortars varying in mix composition, ref. table 3 [2]*

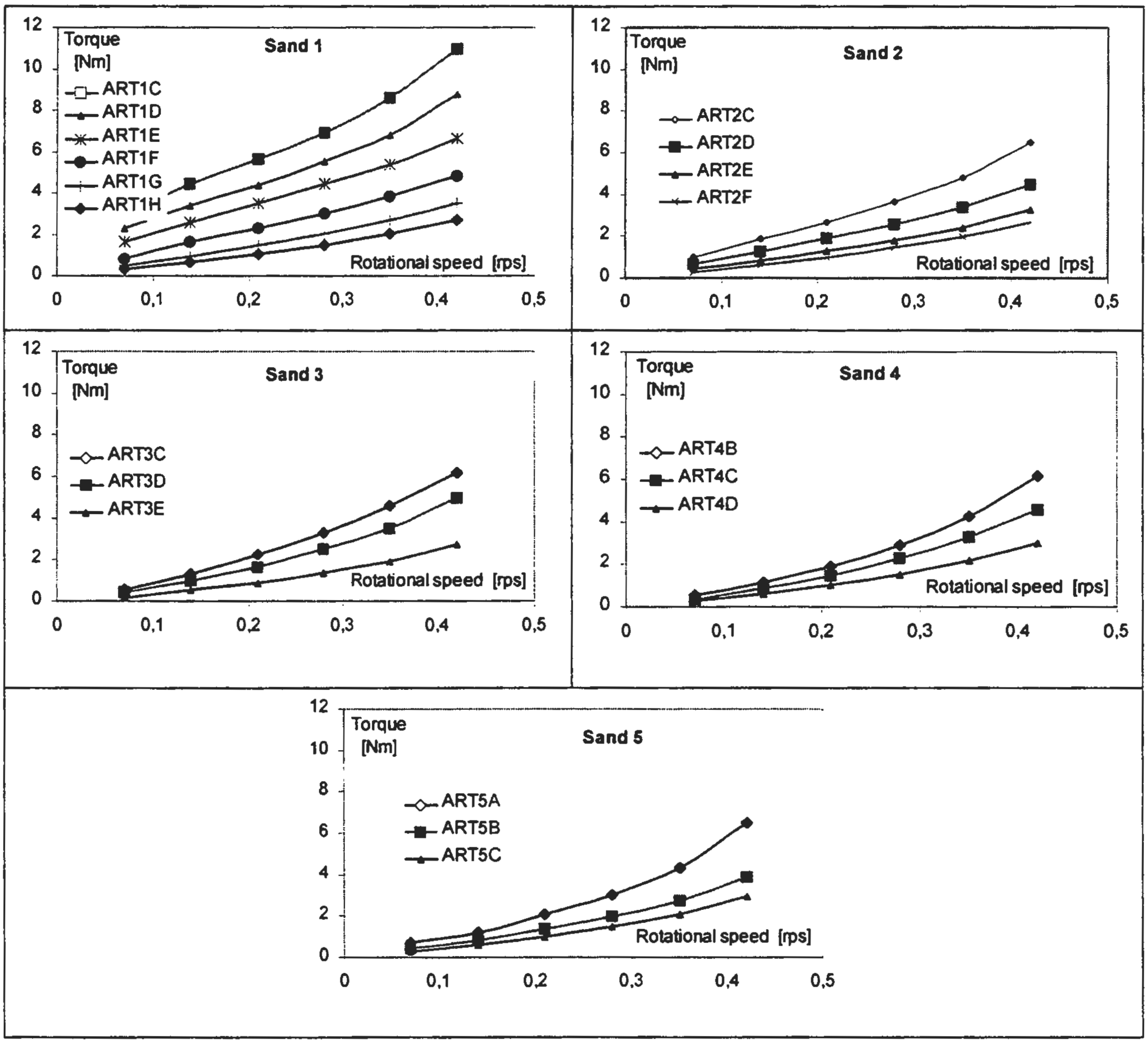

Figure 6: *Influence of mix composition, ref. table 3, on the flow of mortars with artificial sands. [2]*

The results presented in figure 6 shows that the lower the w/c-ratio, the more pronounced is the apparent shear thickening behaviour. This is in contrast to the behaviour of traditional mortars, having Bingham rheological behaviour independent of w/c-ratio.

Figure 7 shows the influence of particle shape, comparing the artificial sands and the natural sands. The mixes selected for this comparison have almost identical rheological properties when the artificial sands are used. All the sands have been water-saturated for 24 hours before mixing. By comparison with figures 5 and 6 it can be seen that this has no influence on the artificial sands. On the other hand, preliminary tests have shown a significant influence for the natural sands, hence this procedure for these measurements.

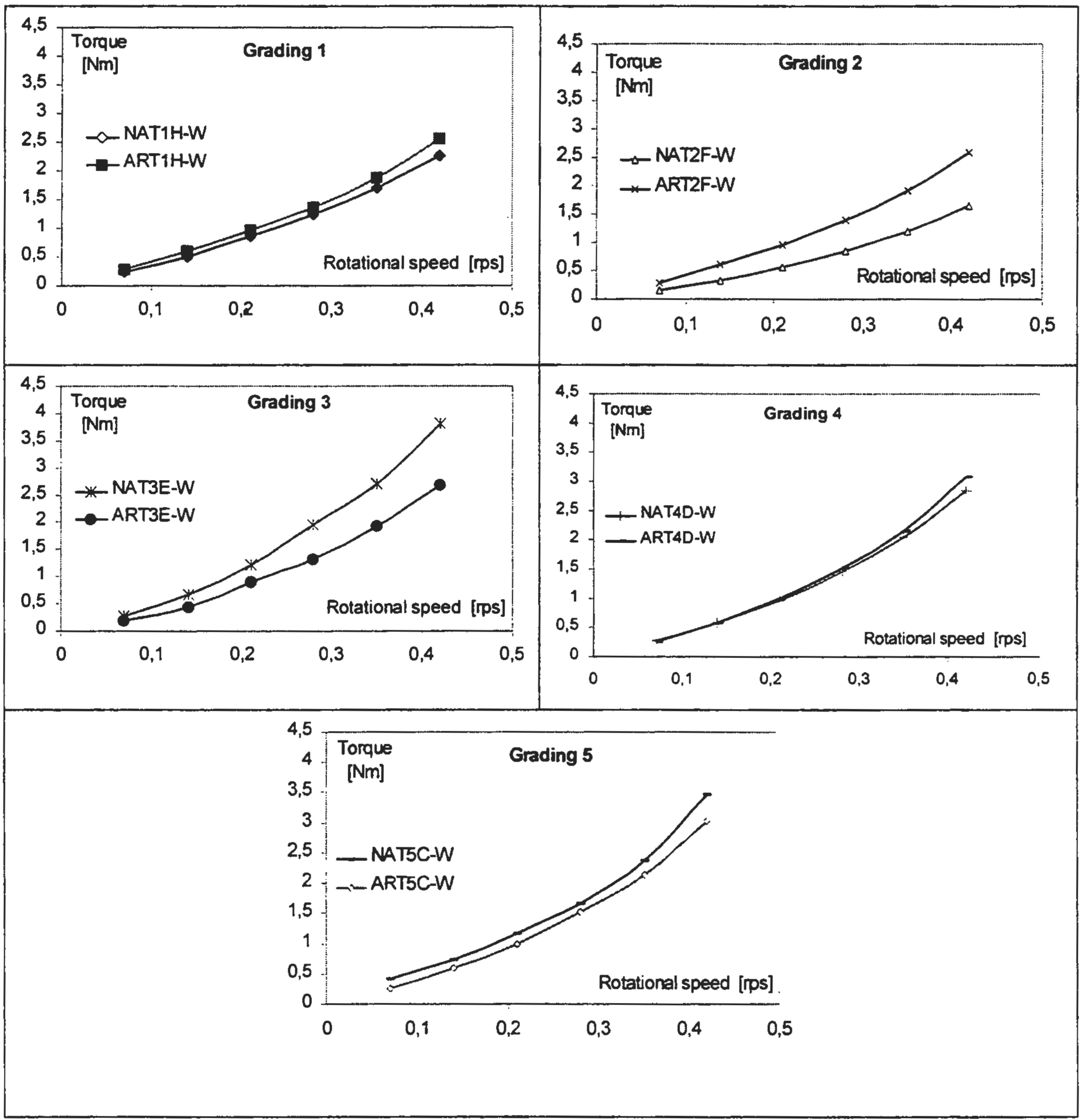

Figure 7 *Influence of sand type, natural and artificial on the flow of mortars. '-w' indicates that the sand has been water-saturated for 24 hours. [2]*

In table 5, the rheological parameters τ_0 (yield stress, Pa) and μ (viscosity, Pas) for the mortars are presented. Only data measured for rotational speed between 0.07 and 0.21 rps have been used for the calculation. As mentioned in paragraph 3.2, the actual measuring set-up might be the reason for the non-physical meaning of negative values for the yield stress. However, we assume that the relative changes in yield stress between mixes have a physical meaning.

Table 5: Rheological parameters: yield stress, τ_0 [Pa] and viscosity, μ [Pas], of mortars with artificial and natural sands. The parameters are estimated from measured torque at rotational speed between 0.07 and 0.21 [rps]. The figures for the natural sands are for the 24 hours water saturated specimens. (See paragraph 3.2 for the explanation for the non-physical meaning of negative values for the yield stress)

Mix type	Parameter	Nat. 1	Art. 1	Nat. 2	Art. 2	Nat. 3	Art. 3	Nat. 4	Art. 4	Nat. 5	Art. 5
A	τ_0										7
	μ										40
B	τ_0								-27		-10
	μ								40		27
C	τ_0		277		24		-48		-34	7	-19
	μ		76		49		49		33	21	21
D	τ_0		209		2		-24	-9	-21		
	μ		60		37		35	19	22		
E	τ_0		125		-5	-38	-30				
	μ		53		26	29	21				
F	τ_0		24	-9	-12						
	μ		42	12	21						
G	τ_0		-1								
	μ		29								
H	τ_0	-14	-6								
	μ	18	21								

5 DISCUSSION

The maximum rotational speed in the BML viscometer used in these measurements is not larger than the ones used for testing ordinary mortars, where apparent shear thickening is not observed. Thus, the apparent shear thickening effect in the present mortars might be a result of the new generation of additives, leading to a more slowly relaxing material than when using traditional types of admixtures or even no admixture. In other tests carried out at the Research and Development Centre / Aalborg Portland, the same effect has been seen on self-compacting concretes. Both for the actual mortars, and the concretes, the borderline between Bingham behaviour and apparent shear thickening could be established to a shear rate of 400 to 450 m/h at the outer surface of the inner cylinder. Measurements being performed as part of an ongoing student project at the Dept. of Civ. Eng. / Tech. Univ. of Denmark supports the assumption of equilibrium not being obtained within 5 sec, which is the often applied time period at each rotational speed when measuring with the BML viscometer.

We expect that the negative values for the yield stress given in table 5 are caused by a combination of the transient time, the sampling time and the data processing. In the present study, the reported torque was taken as a mean of the lowest 10 points, which may give too high values for the torque at the highest shear rates and too low values for the torque at the lowest shear rates as mentioned earlier.

One way to solve this problem could be to prolong the total time at each shear rate, and also prolong the transient time. However, this can lead to segregation of the mix. Therefore the optimum choice for the experimental parameters is a question of choosing between Scylla and Charybdis. This item will be addressed in the nearest future.[7]

From the rheological parameters in table 5 it can be seen that the yield stress, τ_0, (in general) and the viscosity, μ, decrease with decreasing fineness (increasing number of grading) for same particle shape. This was expected according to the findings of Billberg for fine mortar [8].

The influence of changing particle shape and surface texture by replacement of the artificial sand with the natural sands is not as easy to observe as the artificial and natural sands to some extent also vary with regard to fineness and eigenpacking. Table 6 summarises the particle data, ref. table 2, as well as the expected influence and the measured results. The expected change due to variation in eigenpacking is based on the analytical model proposed by Nielsen [9]. Change of particle shape from rounded to angular (increased aspect ratio) is expected to increase both the yield value and the viscosity

Table 6: Expected and measured changes resulting from replacement of artificial sand by natural sand. FM: Modulus of fineness.

		Particle characteristics, ref. table 2			Expected changes		Measured changes	
Grading		ART	NAT	➔	τ_0	μ	τ_0	μ
1	FM	1.38	1.47		Decrease	Decrease	-8	-3
	Eigenpacking	61	65			Decrease		
	Shape 1)	R	R		No change	No change		
	Surface 2)	S	R		Increase	Increase		
2	FM	1.96	1.95		No change	No change	3	-9
	Eigenpacking	63	69			Decrease		
	Shape	R	R		No change	No change		
	Surface	S	S		No change	No change		
3	FM	1.96	2.2		Decrease	Decrease	-8	8
	Eigenpacking	70	69			No change		
	Shape	R	A		Increase	Increase		
	Surface	S	R		Increase	Increase		
4	FM	2.48	2.59		Decrease	Decrease	12	-3
	Eigenpacking	70	70			No change		
	Shape	R	A/R		Increase	No change		
	Surface	S	R		Increase	Increase		
5	FM	2.94	2.97		No change	No change	26	0
	Eigenpacking	66	69			Decrease		
	Shape	R	A		Increase	Increase		
	Surface	S	R		Increase	Increase		

1): R: Rounded, A: Angular
2): S: Smooth, R: Rough

Besides the unexpected change in viscosity for grading 3, the observed trends are as expected. The fineness, the eigenpacking, and the particle shape appear to have a much larger influence than the surface texture of the particles. This is in agreement with the findings of Billberg [8], who found approximately the same yield stress and viscosity in the fine mortars using the same amount of fillers in forms of ground granulated blast furnace slag, flyash, and two types of limestone fillers. These four fillers had nearly the same grading with fineness modulus between 1.33 and 1.43.

The results demonstrate, that it is possible to design self compacting mortars with special rheological properties by proper choice of the constituents. This is illustrated in figure 7. These mortars were made with the same cement and flyash mixture, but different sands. The rheological parameters are adjusted by varying the water/powder ratio. A small change in solid fraction can also influence the result.

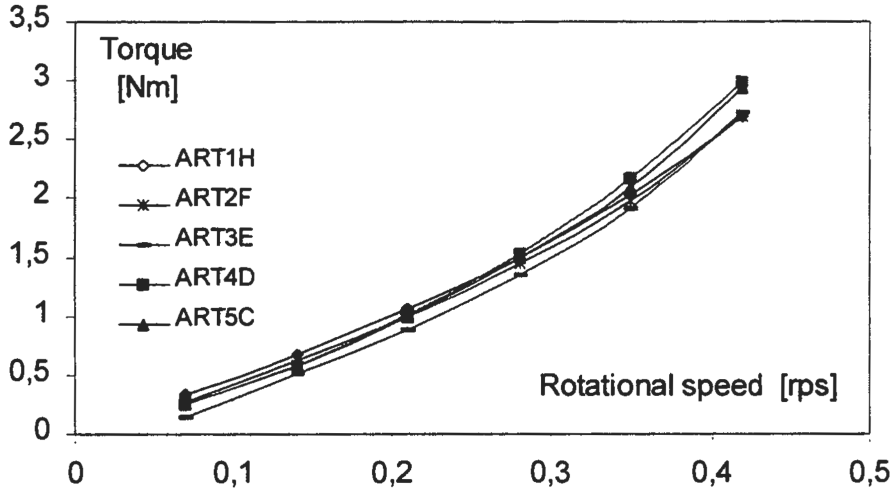

Figure 7: *Five mortars having identical rheological properties. The water/cement ratios varies between 0.35 and 0.42*

6 CONCLUSION

Although the limited number of tests carried out in this project, and hence the lack of statistical significance, the results indicate that

- Increasing fineness of the particles leads to increasing yield stress and viscosity.
- Increasing the aspect ratio leads to increasing yield stress and viscosity.
- The surface texture appears to be of minor importance.

Thus the rheological properties of self-compacting mortars can be tailored for special purposes by choice of cement, fillers and sand.

The new generation of superplastizisers apparently changes the relaxation behaviour of the material. Hence there is an upper limit for the rotational speed or a lower limit for the period of measuring in order to avoid an apparent shear thickening behaviour.

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