THE APPLICABILITY OF THE PARTICLE MATRIX MODEL TO SELF COMPACTING CONCRETE (SCC)

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ABSTRACT

There is a growing interest for low and moderat strength Self Compacting Concrete (SCC) in Norway. In a national research project, the Particle-Matrix (PM) model is used to improve the understanding of the effect of each constituent on the workability of SCC. A laboratory test programme has been performed in order to calibrate the PM model to this concrete type. The preliminary results indicate that the relation between the properties of the constituents and the resulting workability of SCC is unclear. More sophisticated rheological investigations of the matrix materials may improve the understanding of these relations.

KEY WORDS: Self-compacting concrete, Normal strength, Particle-Matrix Model, Fillers, Rheological properties, Viscosity

1. INTRODUCTION

In Norway, SCC was introduced as a "problem solver", i.e. a concrete suited for low access concreting operations, or for structures where smooth and pore free surfaces are required. In general, high strength SCC, based on low w/c ratios and copolymer additives are commonly available. Today, there is an increasing interest for low strength SCC as a cost efficient alternative for construction work characterised by a high production rate and a high degree of repeatability.

In an ongoing national research project, financed by the Research Council of Norway and Norwegian industry, a material model recently developed for ordinary structural concrete is used as a platform for laboratory investigations on low strength SCC. This model, known as the Particle-Matrix (PM) model, describes fresh concrete as a two-phase system. The model is an important tool improving the understanding of the effect of each concrete constituent on the workability of both SCC and ordinary structural concrete.

The laboratory investigations were performed in order to verify the relevance of the material model on SCC, and to investigate the rheological differences between "traditional" high strength SCC and low strength SCC based on filler additions.

2. THE PARTICLE-MATRIX (PM) MODEL

The Particle-Matrix model was developed and verified by Ernst Mørtsell as a part of his dr. ing. thesis /4/. Here, only a brief description is presented. A similar two phase model has earlier been presented by de Larrard /8/.

The workability of concrete is a result of the inherent properties of the constituents, the mix proportions and the physical and chemical interference between them. The simplest possible way of modelling this complex system is to consider the concrete a two-phase material composed of a matrix phase and a particle phase, or described by their properties, a fluid material and a friction material /1/. This model is anticipated to be particularly suitable for self-compacting concrete (SCC) and high performance concrete (HPC), primarily due to the increasing tendency of the concretes to be matrix dominated as the water-powder ratio (w/p) is decreased.

The total surface area and surface properties rather than their mass or angularity governs the effect of the fine aggregate particles on the concrete. If the phases of the PM-model are to be defined according to their properties, and not according to their origin, a rather unusual division of the concrete constituents into these two phases has to be done:

- The matrix phase is defined to consist of the water, possible chemical additives and all fines, including cement, pozzolanes and aggregate fines, i.e. particles < 0.125 mm
- The particle phase is defined to consist of aggregate particles > 0.125 mm

The basic problem then is to describe and determine the properties of the phases in a consistent way, and further to model the impact of these properties when combining the phases in different proportions in concrete mixes. The present approach is based on single parameter characterization of each phase:

- The flow resistance ratio of the matrix
- The air voids modulus of the particles

The flow resistance ratio (λ_Q) is determined in the *FlowCyl* test /1/, a modification of the *Marsh Cone* test, originally developed to characterize oil well cements, but also used to characterize concrete binders /2/. λ_Q is a representation of the difference in flow rate between the test material and an ideal fluid flowing through a vertical, cylindrical steel tube with an outlet formed as a cone ending in a narrow nozzle. The "ideal" fluid has a λ_Q-value of 0.0, while the theoretical upper limit of the λ_Q – value for a viscous fluid is 1.0. Recent results /3/ has shown that λ_Q is closely related to the plastic viscosity, μ, of typical matrix materials.

The air voids modulus (H_m) /1/ is based on the air voids space ratio (measured or calculated) of the fine (0.125 - 4 mm) and coarse (> 4 mm) portions of the particle system. The air voids ratio depends on grading, angularity, mineralogy and surface texture. Hence, at least within limited fractions of the aggregate, the air voids ratio represents the sum of the relevant particle properties with respect to concrete workability. However, the effects of these properties on concrete workability are more expressed for the fine particle fraction than the coarse. Hence, the fineness modulus and the fine/coarse aggregate distribution are introduced as correction factors in the definition of H_m. As a consequence, H_m has no direct physical interpretation. For practical purposes, H_m approximately represents the volume that has to be occupied by the matrix material in order to obtain a "no-slump" concrete. The definition of H_m is described by Mørtsell et al /1/.

The workability of the concrete as characterized by the slump and flow measure is finally expressed as functions of the flow resistance ratio, the air void modulus, and the volume of the matrix. The syntax and use of these functions is described in detail by Mørtsell et al /1/. A complete documentation and verification of the PM- model for ordinary concrete may be found in the dr.ing. thesis of Mørtsell /4/. So far, the PM-model has proven to be a powerful tool for the concrete industry, improving the capability of the producer to maintain an even quality level, and reducing the number of pre-defined recipes necessary to obtain such conformity.

3. SCOPE OF THE INVESTIGATIONS

The scope of the investigations has been to verify the relevance of the PM-model to SCC, and to provide suitable data for calibration of the model to these types of concrete. This calibration includes the replacing of the traditional slump and flow table measures by the specialized "slump-flow" (SF) measure.

Both high strength SCC without additional fillers and low strength SCC with substantial filler additions are included in the investigation. This allows a direct comparison of the effect of the different cement and filler types on the flow properties of SCC.

In order to improve the understanding of the relations between the flow properties of the matrix phase and the workability of the concrete, concrete viscosimetry has been included in the investigation.

4. LABORATORY PROGRAMME

4.1 Matrix parameters

The matrix programme included a limited number of typical SCC material parameters combined into a total of 72 matrix recipes, all characterized by the use of the FlowCyl test immediately after mixing, and after 30 minutes. The purpose of the separate matrix test programme was primarily to establish the necessary database for calibration of the PM model to SCC mix design and test methodology.

Furthermore, the obtained data were used to establish an empirical equation expressing the correlation between each constituent material and the resulting flow resistance ratio. This equation allows the effect of each material parameter on the flow properties of the matrix to be predicted, and may consequently be a useful contribution to the use of the PM-model already calibrated for SCC. Only the results concerning matrices also included in the concrete programme are referred to here.

4.2 Concrete parameters

The parameter variations of the concrete test programme are shown in Table 1. The primary concrete test parameter for calibration of the PM-model is the matrix volume, necessitating a series of 4 mixes having different matrix volumes for each matrix composition. Hence, in order to keep the total mix number at an acceptable level, a strictly limited number of matrix variants were included. Focus was put on two different concrete strength levels:

- ordinary strength concretes based on ordinary portland cement (Norcem Standardsement, denoted OPC), voluminous filler additions (Cementa Minifiller, and crushed limestone from Norcem, Brevik) and co-polymer additives (Scancem SSP 2000 and Scancem VMA), mix 1-16.

- high strength concretes based on high strength ordinary portland cement (Norcem Anleggssement, denoted HS OPC), condensed silica fume (Elkem Emsac, denoted CSF) and co-polymer additives (Scancem SSP 2000 and Scancem VMA), mix 17-28.

In addition, cross reference was established between these two parameter groups simply by replacing OPC by high strength OPC and vice versa in two additional series (mixes 29-31 and 32-35). The range of matrix volumes within each series was adapted after the initial trial mix with 340 l/m^3 matrix content. The obtained flow resistance ratios λ_Q obtained immediately after mixing of each matrix variant are included in the table (data from the matrix test programme).

Please note that the w/p-ratio (water / powder - ratio, filler <0.125 mm included) is in the same range for all concretes, even if the w/b-ratio (water / binder - ratio, filler <0.125 mm excluded) is quite different for the low strength (0.60) and high strength concrete (0.40) types. For the low strength concretes, the added filler may consequently be regarded a cement replacement with respect to workability as compared to the high strength concretes.

The aggregate composition (ie the particle phase, fillers excluded) was exactly the same for all concretes, natural 0-8 mm Årdal granite gravel and 8-16 mm Årdal crushed granite rock. Since the matrix volume varies throughout the test programme, the volume of the aggregate varies correspondingly. This causes a minor variation in the amount of natural fines (particles < 0.125 mm) contributing to the matrix phase. This effect is minimised by defining the matrix composition (with respect to natural filler) from the second or third concrete within each series (1-4, 5-8 etc). The characteristics of the aggregate, sieving curves, the air voids modulus (H_m), densities etc are not reported here.

The air content is not included in the matrix volume. The air volume was kept at a stable, low level (approx.1.5 %) by the use of an anti air-entraining agent. Detailed information on materials, concrete recipes and mixing procedures can be found in the open project reports /5,6/. Some information on the fillers, cements and additives are also given in a paper by Pedersen and Mørtsell, dealing with characterisation of fillers and their effect on the viscosity and yield shear stress of SCC matrices /3/.

4.3 Concrete test procedures and equipment

The workability of the SCC is characterised by the slump-flow (SF-) measure, a non-standardised procedure based on the traditional slump measure. The SF measure is the average diameter of the slump specimen 30 seconds after rapid removal of the steel cone. Normally, SCC is defined to have a SF-measure in the range above 650 mm.

Table 1. Parameter variations

Mix No	w/b	s/c	Cement type	Additive		Added filler **		Matrix	w/p	λ_{Q2}
				Type	Dosage*	Type	Dosage	Volume (l/m^3)		
1	0.60	0 %	OPC	Co-Polymer	1.00 %	Limest.	40 %	330	0.37	0.51
2								340		
3								350		
4								360		
5	0.60	0 %	OPC	Co-Polymer	1.20 %	Limest.	60 %	340	0.33	0.73
6								350		
7								360		
8								370		
9	0.60	0 %	OPC	Co-Polymer	1.00 %	Mini-filler	40 %	340	0.37	0.52
10								350		
11								360		
12								370		
13	0.60	0 %	OPC	Co-Polymer	1.20 %	Mini-filler	60 %	340	0.33	0.72
14								350		
15								360		
16								370		
17	0.40	0 %	HS OPC	Co-Polymer	1.00 %	-	-	310	0.34	0.66
18								320		
19								340		
20								350		
21	0.40	5 %	HS OPC	Co-Polymer	1.00 %	-	-	310	0.34	0.68
22								320		
23								330		
24								340		
25	0.40	5 %	HS OPC	Co-Polymer	1.50 %	Limest.	10 %	300	0.31	0.79
26								310		
27								330		
28								340		
29	0.60	0 %	HS OPC	Co-Polymer	1.20 %	Limest.	60 %	300	0.32	0.74
30								320		
31								340		
32	0.40	0 %	OPC	Co-Polymer	1.00 %	-	-	300	0.31	0.82
33								310		
34								330		
35								340		

w/b: water-binder ratio
s/c: CSF-cement ratio
w/p: water -powder ratio
λ_{Q2}: flow resistance ratio 2 minutes after completed mixing
* Dosage in percent of cement. Stabilizer not included (Co-polymer based stabilizer addeded in a dosage corresponding to 50 % of the SSP)
** Dosage in percent of cement. Natural filler from the aggregate phase not included

In addition, the workability of the concretes is characterised by the use of a BML viscometer /7/, measuring the plastic viscosity and yield shear stress of the concretes according to the Bingham model for fluids.

Both tests were performed immediately after mixing, after 30 minutes and after 1 hour. Here, results obtained immediately after mixing are reported.

5 EXPECTED RESULTS, HYPOTHESIS

Since the air voids modulus (H_m) is kept constant throughout the test series, the workability of the SCC's tested here should be a unique function of the flow resistance of the matrix,λ_Q, and the matrix volume according to the PM model. This expectation is based on the presumption that the FlowCyl test produces data representing all the relevant matrix properties in a consistent way.

The expected principal relations between the matrix volume and the SF-measure are illustrated for two matrices having different λ_Q - values in Figure 1. A more viscous matrix (higher λ_Q) is expected to induce a higher matrix volume to produce certain workability as expressed by the SF-measure.

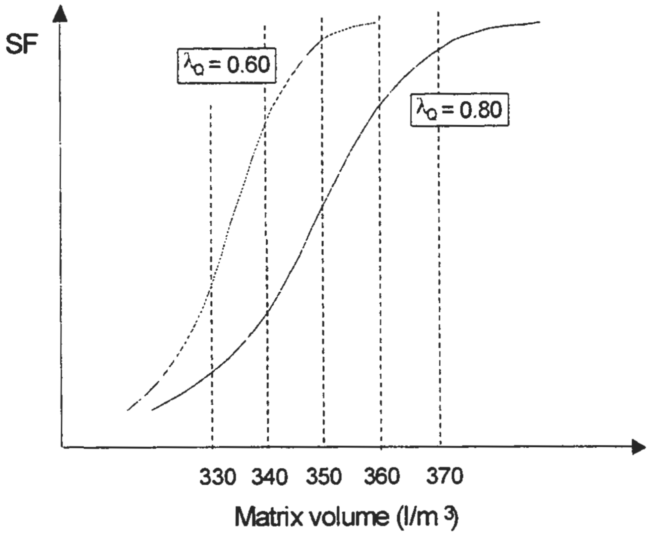

Figure 1. Expected principal relation between the matrix volume and the slump flow (SF) measure for matrices having different flow resistance ratios (λ_Q).

6. RESULTS

6.1 Slump flow concrete tests

In Figure 2, the SF-measure is plotted as a function of the matrix volume for 4 of the series based on OPC and fillers. 3 of these series are low strength concretes with large amounts of fillers added. As expected, the workability increases uniquely with the matrix volume, and the matrix volume necessary to produce certain workability increases with an increasing flow resistance of the matrix material. Different types and amounts of fillers produce differences in workability, as might be predicted from the FlowCyl tests. Consequently, these results are totally in line with the PM model concept. For the test series represented in Figure 2, self compacting ability is obtained at matrix volumes of approx. 340 l/m^3 for matrices having λ_Q – value 0.51, while a λ_Q – value of 0.82 requires a matrix volume as high as 400 l/m^3.

In Figure 3, the SF-measure is plotted as a function of the matrix volume for 4 of the series based on high strength OPC and combinations of CSF and fillers. Again, the workability is uniquely related to the matrix volume within each test series. Surprisingly, according to Figure 3, a more viscous matrix as expressed by a higher λ_Q – value does not necessarily imply need for an increased matrix volume to obtain self-compactability.

The most noticeable result, however, may be observed comparing Figure 2 and Figure 3. At a slump flow measure of approx. 650 mm, the necessary matrix volume is 40-80 l/m^3 lower for the concretes based on high strength OPC than for the concretes based on OPC, all other parameters comparable. Such a difference in workability properties between different cement types is not necessarily unusual, and may be related to the cement chemistry and fineness. Here, however, no indication of this dramatic workability difference was found testing the corresponding matrices. Actually, the flow resistance ratios (λ_Q) are basically within the same range.

Even when adding as much as 60 % limestone filler at a w/c-ratio of 0.60, the use of the high strength OPC generates a reduced need for matrix volume of 50 l/m^3 to obtain a SF-measure of 650 mm as compared to the corresponding OPC concrete. The λ_Q – values are practically the same (approx 0.74) for the respective matrices. Hence, other properties than the matrix viscosity must be responsible for these remarkable differences in concrete workability properties.

The missing consistency of the results raises a number of questions:

- Does the slump-flow measure give an incomplete picture of the SCC workability?
- Why doesn't the FlowCyl test on matrices reflect the differences in concrete workability?
- How can the type of cement induce significant differences in concrete workability when a replacement of cement by filler has very little effect?
- Does the PM model concept neglect important information about concrete workability parameters?

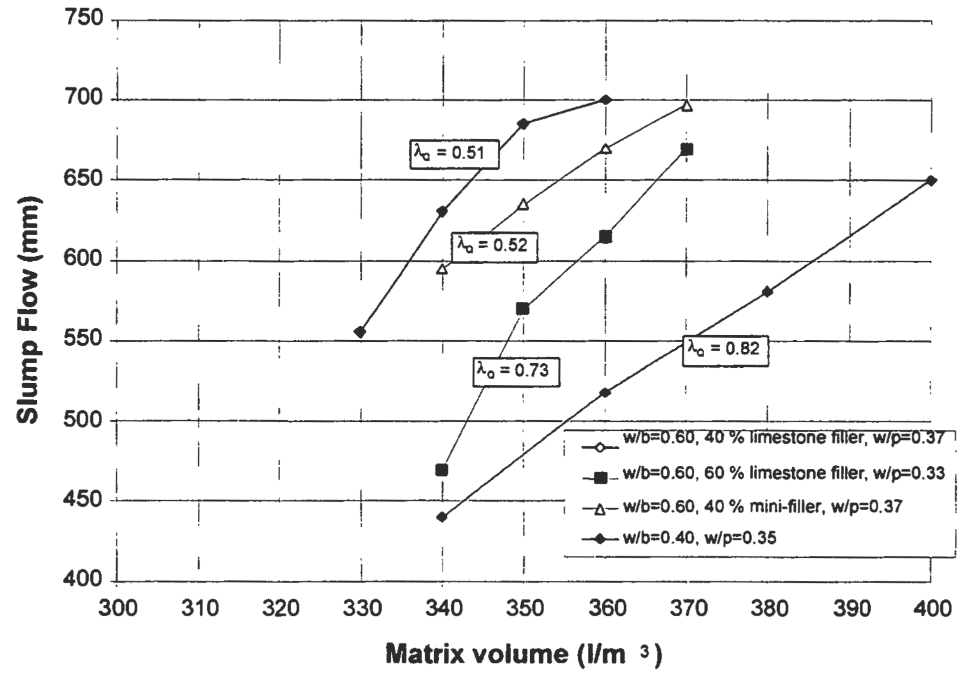

Figure 2. Slump Flow measured immediately after mixing for 4 series of concretes based on OPC and fillers. The matrix composition is constant within each series; only the matrix volume is varied.

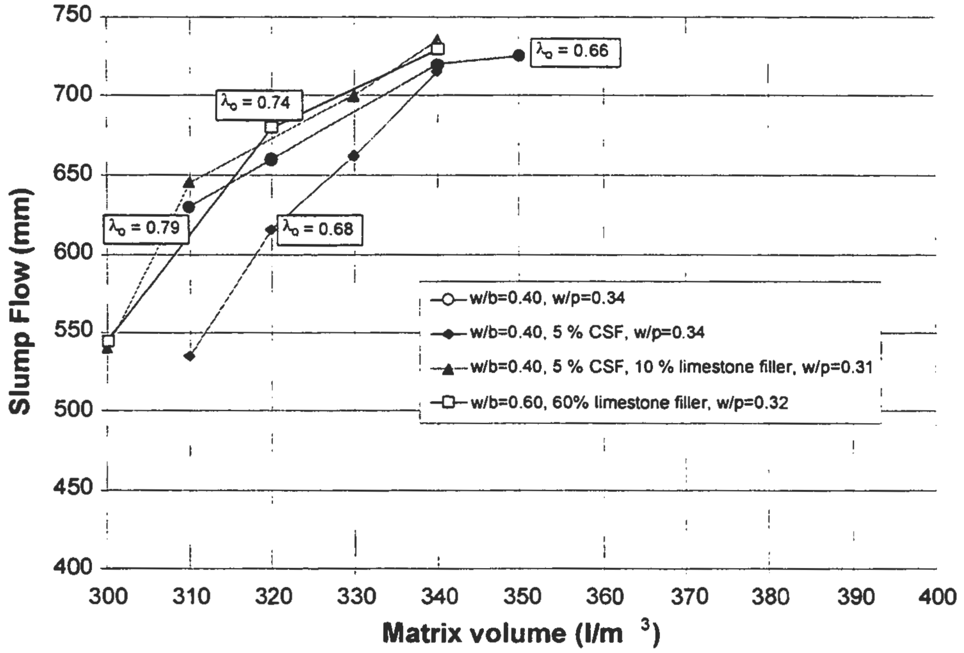

Figure 3. Slump flow measured immediately after mixing for 4 series of concretes based on high strength OPC and combinations of CSF and fillers. The matrix composition is constant within each series; only the matrix volume is varied.

6.2 Viscometer tests

In Figure 4, the plastic viscosity as measured by the BML viscometer immediately after mixing is plotted as a function of the matrix volume for 4 series of concretes based on combinations of OPC and fillers. As expected, an increased matrix volume leads uniquely to a reduced concrete viscosity within each series. For the OPC concretes, an increased matrix flow resistance ratio (λ_Q) induces a higher concrete viscosity, as also could be expected from the SF measurements (Figure 2).

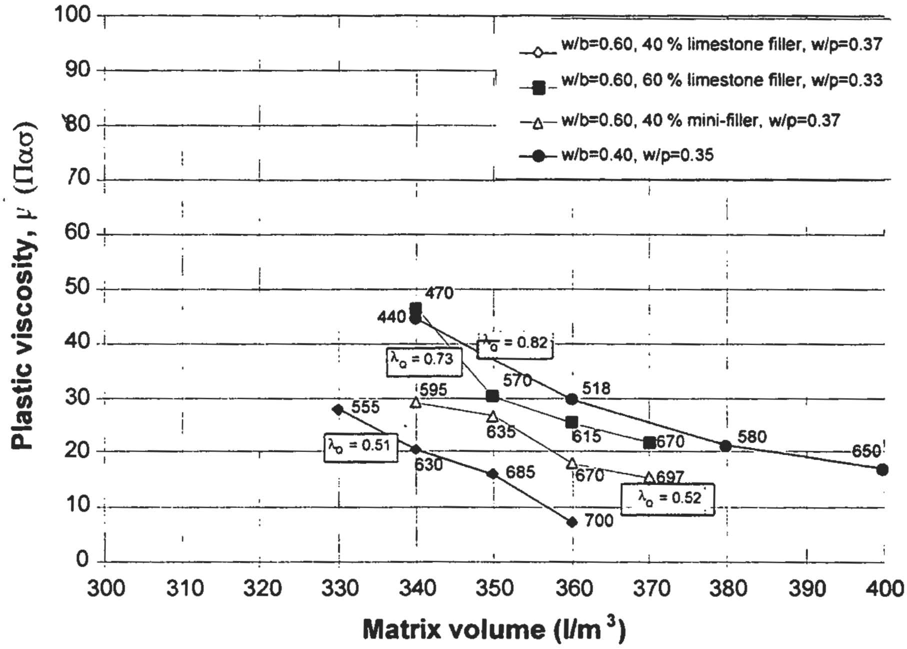

Figure 4. Plastic viscosity measured immediately after mixing as a function of the matrix volume for 4 series of concretes based on combinations of OPC and fillers. The matrix composition is constant within each series; only the matrix volume is varied. The data labels are the corresponding SF-measure in mm.

The corresponding data for the concretes based on high strength OPC in combination with CSF and fillers are plotted in Figure 5. The plastic viscosity of the concretes decreases with an increasing matrix volume within each series as for the OPC concretes. Here, the plastic viscosity does not seem to be directly related to the flow resistance ratio of the matrices. At a matrix volume of 310 l/m^3, the lowest plastic viscosity is actually registered in the concrete series based on the matrix having the highest flow resistance ratio.

Even if there is a significant difference between the concretes based on OPC and high strength OPC also when characterised by plastic viscosity, the difference is not by far as obvious as when expressed by the slump flow measure (Figure 2 and Figure 3). This indicates that other fundamental properties than the viscosity play an important role for the flow properties of these SCC.

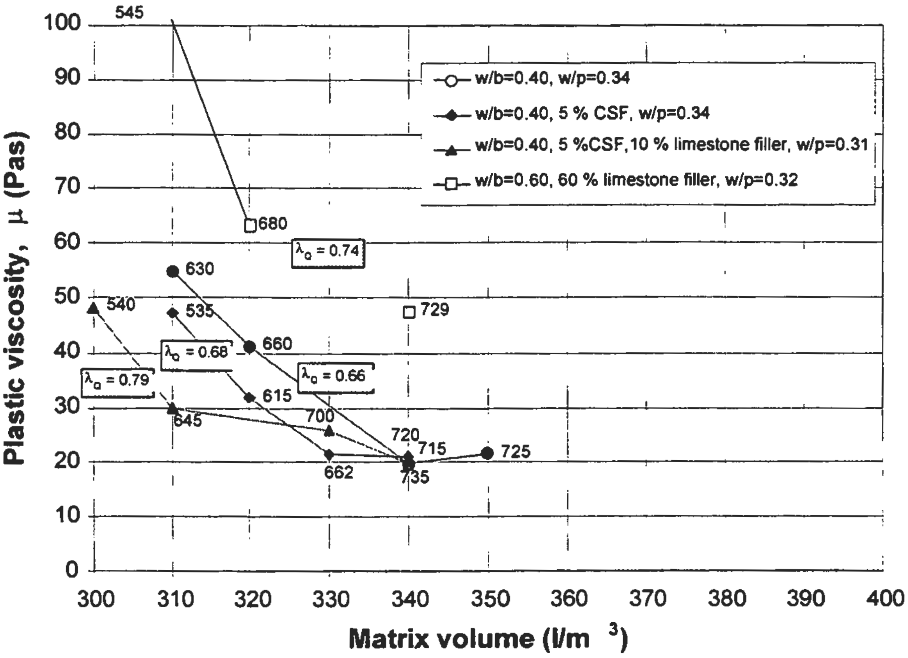

Figure 5. Plastic viscosity measured immediately after mixing as a function of the matrix volume for 4 series of concretes based on high strength OPC. The matrix composition is constant within each series; only the matrix volume is varied. The data labels are the corresponding SF-measure in mm.

In Figure 6, the yield shear stress is plotted against the matrix volume for the 4 series of concretes based on combinations of OPC and fillers. The concretes having self-compacting properties, i.e. SF- measures higher than 650 mm, have a practically negligible yield shear stress. Hence, the viscosity of these concretes is decisive for the workability. When the matrix volume is reduced to approx. 340 l/m^3, however, the yield shear stress tends to increase dramatically. This increase coincides clearly with the loss of workability associated with the reduced SF-measure.

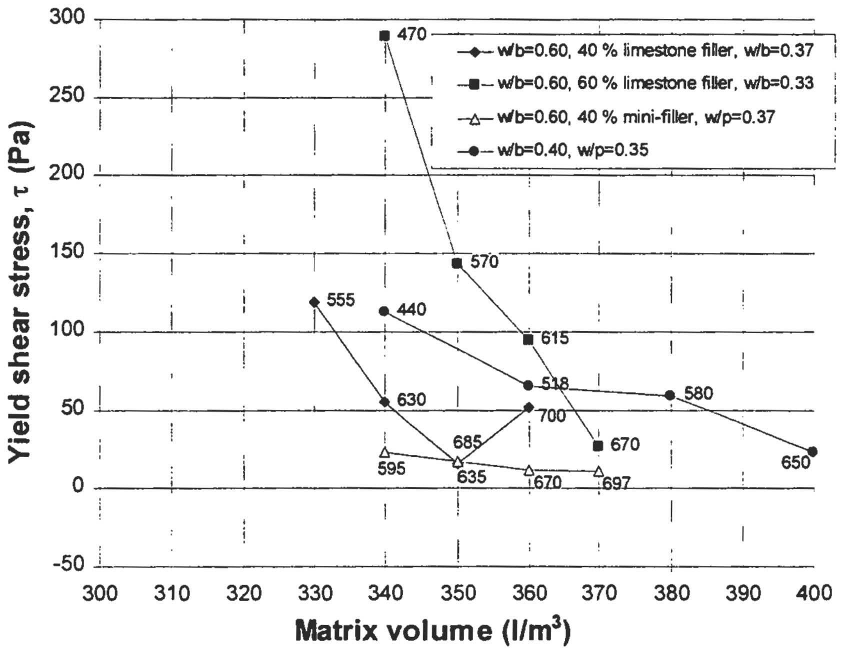

Figure 6. *Yield shear stress measured immediately after mixing as a function of the matrix volume for 4 series of concretes based on combinations of OPC and fillers. The matrix composition is constant within each series; only the matrix volume is varied. The data labels are the corresponding SF-measure in mm.*

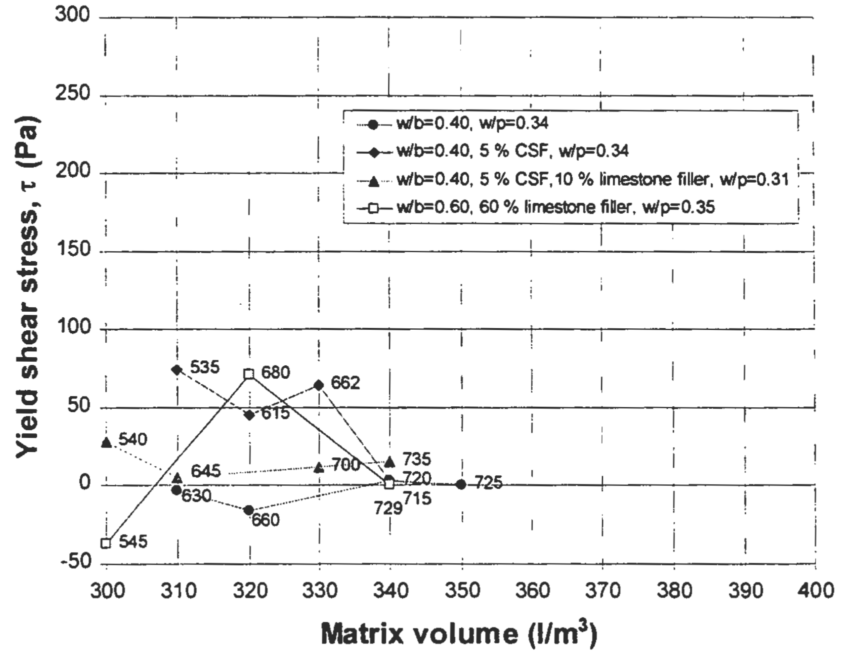

Figure 7. *Yield shear stress measured immediately after mixing as a function of the matrix volume for 4 series of concretes based on high strength OPC. The matrix composition is constant within each series; only the matrix volume is varied. The data labels are the corresponding SF-measure in mm.*

A similar relation between the matrix volume and the yield shear stress has not been found for the concretes based on high strength OPC in combination with CSF and fillers, see Figure 7. Even at very low matrix volumes, and SF-measures well below 650 mm, the yield shear stress is insignificant for these concretes. Hence, the reduced SF-measures of the high strength OPC concretes must be caused by the increased viscosity (see Figure 5), probably associated with an increased particle interference (due to increased particle concentration).

7. DISCUSSION AND CONCLUSIONS

Since the composition of the particle phase is exactly the same in the concretes based on OPC and high strength OPC respectively, the observed differences with respect to the yield shear stress at low matrix volumes must be related to differences in the matrix properties. The FlowCyl test is apparently insensitive to these rheological differences. Consequently, at the moment, no simple correlation between the matrix properties and the concrete yield shear stress has been identified.

The preliminary hypothesis is that small, but still significant differences in yield shear stress in the matrix materials must be responsible for the observed differences in concrete properties. These differences must then be highly sensitive to the particle concentration when the matrix materials are combined with a particle system to full concretes. The results indicate that the type of cement is of crucial importance for the matrix property responsible for the observed differences in SCC workability. The type of additives may possibly also play an important role.

Since only the series of concretes based on combinations of OPC and fillers are suitable for calibration of the PM model, such calibration has not been performed. Hence, the hypothesis illustrated in Figure 1 has not been verified for SCC. In order to obtain full relevance of the PM model for SCC, the FlowCyl test must most likely be replaced by a matrix test able to detect the matrix properties related to the concrete yield shear stress.

A research programme involving more fundamental tests of the rheological properties of matrix materials has been initiated, and preliminary results from this investigations are presented by Pedersen and Mørtsell /3/. Furthermore, the concrete test programme will be extended, including alternative materials and material combinations in order to verify the general relevance of the observations presented here.

Since the SF test seems to be sufficiently sensitive to both the viscosity and the yield shear stress as measured by the BML viscometer, this very simple procedure must be regarded relevant as a general a workability criterion for SCC. However, the very strong observed effect of the yield shear stress on the SF-measure may be an indication that the normal SCC acceptance criterion of 650 mm may be too rigorous in situations where the yield shear stress has only minor effect on the performance of the concrete, f. ex. when placing the concrete by pumping.

8. ACKNOWLEDGEMENTS

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