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Packing and Aggregate/Fibre – Void Saturation to Proportion Self-Compacting Fibre Reinforced Concrete

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ABSTRACT

Required quality and volume fraction of lubricating cement paste, V_p, or matrix, V_m, (pozzolan- and filler modified paste) is affected by fibre. Thus, sustainability is affected since consumption of binder materials affects sustainability. Packing (C) (or void content (1-C)) of fibre-aggregate particle mixes was therefore measured, analyzed and calculated from relations between angular particle shape and particle void fraction (1-C). A modified compressible packing model was applied and the compaction factor determined. The relation aggregate-void saturation ratio (V_p/(1-C), V_m/(1-C) vs rheology of fresh self compacting fibre concrete mixes was investigated showing that increased aggregate/fibre – void saturation ratio relates to increased slump-flow and reduced plastic viscosity. Also reduced slump-flow time and yield related to void saturation. Thus a relation between the basic proportioning parameters particle packing, volume fraction of lubricating matrix phase and the rheology of fresh concrete was indicated when proportioning with the particle-matrix approach at relatively high packing fractions.

INTRODUCTION

The sustainability of concrete structures relates to consumption of non-renewable raw materials and energy, associated emissions and also the contribution to growth of a sustainable society (improved working environment, infrastructure leading to increased human welfare etc) [UN 1987, Proc Lillehammer 2007]. The basic sustainability concept was therefore translated into how cement and concrete materials can be engineered to contribute to a sustainable development [Proc Lillehammer 2007, Int Expert Worksh 2008, Norwegian Concrete Assoc. 2009]. Minimizing both consumption of binder powder per cubic metre of concrete and total consumption of concrete will contribute to a sustainable development with the present huge annual worldwide concrete consumption; in the order of 6 km^3 [Norwegian Concrete Assoc. 2009], and its associated effect on sustainable development.

The use of self compacting or highly flow-able fibre reinforced concrete is a way of improving the working environment of the concrete industry [Nielsen 2007], also contributing to a sustainable development. With continued research efforts within its constituents, proportioning, fresh and hardened properties we believe it will improve the sustainability of concrete structures [Kanstad 2008].

In this paper the relation between basic proportioning parameters and the rheology of fresh fibre concrete are further investigated to deal with the negative effects on rheology of fibre suspensions and fresh concrete [Björkman 2008a,b, Vikan 2008]. Furthermore, we aim to proceed in the understanding of how aggregate particles, fibres and their angularity affect particle packing and rheology [Geiker et al 2002, Bui et al 2003, Berg and Jacobsen 2008] to proceed in the development of proportioning methods of fibre reinforced self-compacting concrete.

PACKING OF AGGREGATE/FIBRE MIXES

Packing. The packing, C, of loose particles (aggregate, fibre) in a specific arrangement after some predefined compaction is simply defined as the volume fraction of solid. Together with the volume fraction of voids, ε, they make up a unit volume:

$$C + \varepsilon = 1 \tag{1}$$

This simple relation has been applied for a long time in the proportioning of concrete. In [Feret 1892] C was used to determine the amount of cement and water necessary to fill up the void space between different combinations of aggregate particles. Nomograms for C were made from measurements of packing on a number of combined aggregates. Later, a number of reviews, experimental and model studies have been made [Powers 1968, Stovall et al 1986, Johnston 1990, Glavind et al 1993, deLarrard 1999]. These contributed significantly to advance the proportioning of concrete. From the early application of steel-fibre concrete [Edgington et al 1974, Maage 1976, Hannant 1977] a number of studies were made with varying approaches to proportion fibre concrete with adequate rheological properties and these have been reviewed [Grunewald 2004].

The increased probability of particle collisions due to fibre rotation [Björkman 2008a,b] and increased void space due to fibres is the reason for that steel fibre increases the demand for paste volume or mortar to keep a certain workability or concrete flow, see figure 1 [Barthos et al 1996]. However, as seen from the figure, fibres might in fact also reduce the void space and thus the effect on packing and on rheology is not straight forward. We showed how to calculate whether fibre in aggregate increases or reduces packing [Berg and Jacobsen 2008].

Fig. 1. Packing Affected by Fibre Depending on Size Ratio [Barthos 1996]

There is thus a risk that the use of fibre concrete might increase the consumption of binder and reduce sustainability. Consequently, in addition to work on obtaining more slender and thus less material consuming structures with fibres [Kanstad 2008] steps must thus be taken to ensure optimum paste volume with respect to rheology, while keeping the binder consumption as low as possible.

This paper therefore further investigates the relationship between packing of aggregate-fibre mixes and the volume of cement paste, V_p, or filler modified paste (matrix), V_m, necessary to obtain sufficient aggregate-void saturation ratio. The latter is the volumetric ratio between lubricating phase and volume of voids in a mix of particles compacted in a specific way:

$k' = V_p/(1-C)$, $K' = V_m/(1-C)$, $k'' = (V_p-V_{air})/(1-C)$, $K'' = (V_m-V_{air})/(1-C)$ etc (2)
and $k = V_p/[(1-C)V_{tot}]$ so the term maximum packing fraction, (Φ/Φ_m) with $\Phi_m = C$ gives

$$k = \frac{V_p}{(1-C)V_{tot}} = \frac{1-\Phi}{1-\Phi_m} \qquad (2a)$$

C may be calculated or measured for total aggregate or for a certain fraction, for example considering a two-phase approach with particles (fibre and aggregate) > 0.125 mm. We could then regard the lubricating matrix phase as cement paste and filler < 0.125 mm [Mørtsell 1996, Smeplass&Mørtsell 2003] and only consider the real packing of particles > 0.125 mm. This is probably different from the apparent packing determined in [Jacobsen and Arntsen 2008] that was simplified by subtracting the solid filler volume from the packing value measured on the total aggregate.

The aggregate-void saturation ratio has proven useful in proportioning of various types of concrete [Johnston 1990, Jacobsen et al 2005, Jacobsen & Arntsen 2008]. Note that also the air void content of the lubricating phase has a large effect on rheology [Powers 1968] so that the air void content of the two phases V_p and V_m should be considered, giving at least four different aggregate void saturation ratios that hopefully relate to fresh concrete properties [Jacobsen & Arntsen 2008]. Note that the aggregate void saturation approach is quite similar to the equivalent paste thickness concept [Powers 1968, Bui et al 2003, Reinhardt & Wüstholz 2008]. It is however easier to verify experimentally so that we hopefully can establish simple relations between proportioning parameters and resulting rheology.

Modeling. In [Berg 2007, Berg and Jacobsen 2008] the effect of angularity of particles on packing was reviewed and some equations relating particle shape and packing modified. Furthermore, the prediction of packing of varying commercially available steel fibres for concrete was investigated when packed alone and in mixtures of aggregate and fibres. The basic geometrical quantities were identified; sphericity Ψ = specific surface diameter/volume diameter, angularity of particle $1/\Psi$ [Powers 1968] and equivalent packing diameter, d_p, [Yu et al 1993, Zhou et al 1996] which is the diameter of a sphere not affecting the packing of a mixture of angular particles with angularity $1/\Psi$(which is 1 for a sphere). Then simple expressions for relations between increasing angularity $1/\Psi$ and reduced packing C were identified using experimental data on various fibres and reviewed packing of only fibre. By the use of d_p the packing of particle-fibre mixtures were calculated using some relatively simple analytical equations for binary and multi-component packing [Westman 1936, Yu et al 1993, Zhou et al 1996, Grunewald 2004]. The models could fit experimental packing of aggregate – fibre mixes [Berg and Jacobsen 2008].

Now, the compressible packing model (CPM) [deLarrard 1999] has been modified to be able to calculate packing of multi-component aggregate-fibre mixes treating fibres with the above approach. The model was extended by introducing fibre as a volume fraction of particles with equivalent packing diameter d_p and determining C of the aggregate-fibre mix by solving for C from eq (3) by [de Larrard 1999]:

$$K = \sum_{i=1}^{n} \frac{y_i / \beta_i}{1/C - 1/\Gamma_i} \qquad (3)$$

n: number of fractions

y_i = volume fraction of the ith fraction to solid volume of total particle mix (including volume of fibre with size d_p)

Γ_i = virtual packing of particle mix with dominant fraction i, taking into account wall- and dissolving effects that both depend on size ratio between adjacent fractions and virtual packing of each fraction, see below. Equation from [deLarrard 1999] not shown here.

K = compaction factor, a measure of the compaction energy applied to the mix to reach C.

β_i = virtual packing of fraction i which may be simplified from eq.(3) for a single fraction [de Larrard 1999] into eq.(4):

$$\beta_i = \left(1 + \frac{1}{K_{fraction}}\right) C_i \qquad (4)$$

$K_{fraction}$ = compaction factor resulting from the compaction procedure on single fractions

C_i = packing measured on fraction i.

An excel sheet was developed solving C implicitly from eq. (3) with β_i from eq.(4) and C_i measured on fraction i.

CPM verification from review. A series of calculations were made to compare the model with measured data of packing on aggregates and mixtures of aggregate and fibre reviewed in [Berg and Jacobsen 2008], confirming the findings [Grunewald 2004]; that CPM gives improved packing calculation of fibre/aggregate mixes compared to linear packing theory [Stovall et al 1986, Glavind et al 1993, Nielsen et al 2001] and the analytical binary and multi-component models [Berg &Jacobsen 2008], see figure 2 and 3.

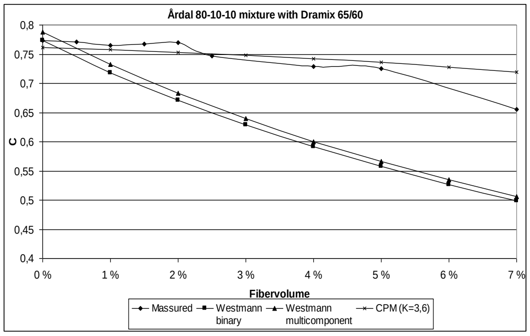

Fig. 2. Packing of 80-20 Sand (0-8mm)-Gravel (8-16mm) Mix With Varying Volumes of Fibre measured and calculated

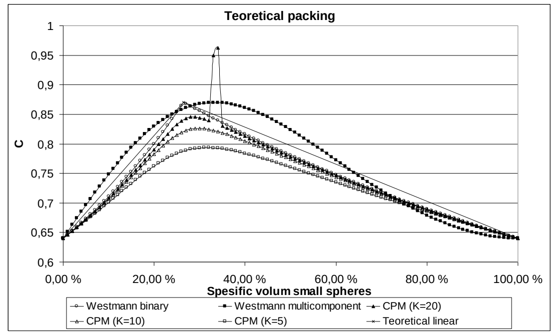

Fig. 3. Packing of Binary Mix of Spheres Analytically [Westman 1936] and With CPM [deLarrard 1990]

The compaction factor K is a measure of the energy required to compact a mix, and should vary in the order 4 - 9 from loose to hard compaction of pure aggregate [deLarrard 1999]. For mixes with fibre the best fit was found at K = 3.6 like in [Grunewald 2004] who used quite hard compaction compared to the experimental data of [Sandbakk et al 2007] in figure 2. Apparently K is "out of scale" for steel-fibre aggregate mixes and we have therefore investigated this further below. Figure 3 shows that CPM is better than the multicomponent analytical model for determining packing of a binary mix of spheres with (d_{small}/d_{large}) = 0.001 but it requires quite high K.

Experiments to determine the compaction factor for aggregate-fibre mixes. A series of experiments were carried out measuring packing of various aggregate fractions that were later combined without and with fibres and also used in concrete. All aggregates were tested loosely packed by filling a solid steel container with H/D = 300/150 mm carefully in three layers and determining bulk volume. Then the aggregates were tested in compacted condition following vibration with 3.1 kPa for 1 minute with additional filling after 30 and 45 seconds. Table 1 shows measured packing of the individual fractions. These were sieved from the 5 aggregates of table 2, which shows the measured packing. The granitic aggregates from Årdal Norway were a mix of natural and crushed with cubic/rounded shape, 0.5 % absorption by weight (coarse) and 0.8 % (fine) and particle density 2670 kg/m^3.

Table 1. Packing Measured on Individual Fractions, from Aggregates in Table 2

d_{aver} (mm)	Fraction (mm)	C_{loose}	$C_{compacted}$
0.063	0-0.125	0.461	0.627
0.188	0.125-0.25	0.504	0.571
0.375	0.25-0.5	0.524	0.599
0.75	0.5-1	0.530	0.606
1.5	1-2	0.538	0.612
3	2-4	0.545	0.618
6	4-8	0.557	0.626
9.6	8-11.2	0.566	0.631
13.6	11.2-16	0.568	0.634

Table 2. Packing Measured on Different Aggregate Sizes

No.	Size (mm)	C_{loose}	$C_{compacted}$
1.	0 – 2	0.606	0.724
2.	0 – 8 high fines	0.642	0.759
3.	0 – 8 washed	0.628	0.739
4.	8 – 11 washed	0.576	0.638
5.	11 – 16 washed	0.574	0.643

The narrow fractions presented in table 1 have compacted packing closer to the maximum packing of randomly mixed mono-sized spheres ≈ 0.64 [Torquato et al 2000] the larger their absolute size, i..e. the more close to monodisperse packing they get. (Face centred cubic packing of spheres is the densest possible packing with max C = 0.7405 [Sloane 1998]). This indicates adequate measuring procedures, except for the finest fractions which obviously are more difficult to handle in bulk state than coarser particles. C for aggregates Nos. 4 and 5 in table 2 are very close to 0.64, but this is probably due to over and/or under sizes compared to the fractions with $d_{average}$ of 9.6 and 13.6 mm in table 1. Some investigations were made on wet packing of the finest fractions applying a new method [Kwan&Wong I II] which is probably better for fines although a quite different procedure from dry packing. In addition, packing will be counteracted increasingly by inter-particle forces that increase inverse proportionally to the particle size [Bache 81]. For this reason, and possibly due to more angular shape of the particles of the smallest fractions, the packing arrangement is looser the smaller the aggregate particles. In the investigations of concrete rheology we have tempted to resolve this by applying the particle-matrix model [Mørtsell 1996, Smeplass et al 2003] including all material < 0.125 mm as part of the lubricating phase and all material > 0.125 mm as particle phase and calculated the packing of particles > 0.125 mm.

The investigated fibres were Dramix 65/35 and 65/60 ((L/D = 65 and length 35 and 60 mm respectively). After careful removal of the glue bundling the steel fibres together and cleaning thoroughly, the loose fibre (eigen) packing was measured at 0.07 for both types. Their equivalent packing diameters d_p = 15 and 26 mm respectively but with equal angularity $1/\Psi = 3.08$ due to their diameters of 0.54 and 0.92 mm respectively. The 65/60 is a relatively large steel fibre that could be used for load carrying structures [Kanstad 2008]. A series of combinations of aggregate and aggregate-fibre particle mixes were investigated as shown in table 3 to determine K for aggregate fibre mixes. Table 3 shows the measured packing on loosely and compacted mixtures of aggregates and fibres.

Table 3. Combinations of Aggregate and Fibre Investigated

No.3	No.4.	No.5	D65/35 (v-%)	D65/60 (v-%)	C_{loose}	$C_{compacted}$
60	20	20	0	0	0.694	0.801
60	20	20	+1.5	0	0.639	0.774
60	20	20	+3	0	0.554	0.753
60	20	20	0	+1.5	0.649	0.789
60	20	20	+1.5	+1.5	0.540	0.737

Table 3 shows the reduced packing by introducing fibres. In 1 m^3 of loose particles the reduced packing at most makes up an increased void space of 154 litres (uncompacted) and 64 litres (compacted) when using 1.5 vol-% of each fibre type. This figure is in the same order as the reduced packing observed by [Barthos&Hoy 1996, Grunewald 2004, Berg 2007, Berg&Jacobsen 2008]. There is little effect on packing of mixing the two fibres compared to using the same volume fraction of one of them due to their large and similar d_p and equal eigen packing of 0.07.

CPM calculations determining the compaction factor K. Calculations were first made with the CPM to determine the compaction factors of the individual aggregates 1 – 5 of table 2 based on the individual fractions of table 1. Then the K of the combined aggregate fractions without and with varying amounts and types of fibres shown in table 3 were determined. Table 4 shows the resulting compaction factors. We see that the main effect on K is from compaction. Compacted mixes require higher K than loose mixes to be able to fit calculated packing in accordance with [deLarrard 1999]. There is no clear effect on K of adding fibre, neither for loose nor compacted mixes. Furthermore, in table 4 neither type of fibre nor dosage of fibres (1.5 - 3 vol-%) gave any effect on K. In the further investigation on the effect on rheology of particle packing the parameters of tables 3 and 4 have been used. The last mix without filler was made for the purpose of producing concrete with true packing and aggregate void saturation ratios by determining the packing of fibres and aggregate particles > 0.125 mm lubricated by a matrix phase with particles smaller than 0.125 mm (as opposed to the apparent packing of the particle phase used in [Jacobsen &Arntsen 2008]).

Table 4. Compaction Factors (K) from CPM Calculations to Fit Real Packing

Particle mix	Fibre	Compaction	K_{mean}	K_{min} - K_{max}
Aggregate 1- 5	0	Loose	1.3	0.8 - 1.8
60-20-20 mix	0	Loose	2.5	-
Aggregate 1- 5	0	Compacted	3.7	3 - 4.8
60-20-20 mix	0	Compacted	6.5	-
60-20-20 mix	1.5-3	Loose	2	1.5 - 2.2
60-20-20 mix	1.5-3	Loose	2.3*	2 – 3
60-20-20 mix	1.5-3	Compacted	4.8	4 - 6.7
60-20-20 mix	1.5-3	Compacted	7*	6 – 9
60-20-20mix >0.125**	1.5-3	Compacted	4.3	3.6-4.8

* calculated without wall effect, ** contains only material > 0.125 mm

RHEOLOGY OF CONCRETE WITH VARYING VOID SATURATION

Concrete materials and mixes. The relationship between the aggregate void saturation ratio, eq. (2), and the rheology of fresh concrete was investigated on a limited number of concrete mixes. The packing of aggregate particles > 0.125 mm and fibres was controlled as described above and the quality of the lubricating matrix phase was kept constant while varying its volume fraction according to [Mørtsell 1996, Smeplass et al 2003]. Thus the aggregate void saturation ratio (eq.(2)) varied for all investigated mixes, see table 5.

The aggregate composition was from table 3. The cement was a Norwegian Norcem Heidelberg CEM II with 20 % fly ash ground with the clinker to a blaine of 450 m^2/kg. The average particle density was 2950 kg/m^3. The silica fume was Elkem grade 940 and the admixtures were Sika ECO 20 and Glenium 151. The filler < 0.125 mm was sieved from sand Nos. 1 and 2 in table 2 and added to keep the matrix phase composition constant: effective w/b = 0.45, CSF/b = 0.05, 3.8 vol-% filler and 1.9 % admixtures by weight of binder. The low amount of filler gave quite high contents of fly ash cement; 430 kg/m^3 at 360 litres of matrix phase per m^3 and 484 kg/m^3 at 405 litres. Concretes were prepared in a 50 litre Eirich counter current mixer. Table 5 shows the investigated mixes

Table 5. Composition of Self Compacting Fibre Reinforced Concrete

Mix	V_{matrix}*	V_{paste}*	Fibre **	$(V_m-V_{air})/(1-C_{>0.125})$***
03	360	347	-	1.689
04	370	358	-	1.735
F01	385	373	0.92	1.627
F02	395	383	0.91	1.669
F03	405	394	0.89	1.712

*: litre/m^3 , **: vol-% of concrete, ***:K=4.75

Measuring rheology of fresh concrete. The rheological properties of fresh concrete were characterized visually and measurements of slump flow (mm) and –time (T500 - sec) with J-ring [EU SCC Guide 2005, Norw Concrete Ass 2007]. The BML coaxial viscometer was used to measure acting shear stress τ_0 (Pa) as function of rate of shear $\dot{\gamma}$ (s^{-1}) giving yield stress (τ_0 – Pa) and plastic viscosity (μ – Pa·s) according to the Bingham model [Tattersall and Banfill 1983, Wallevik 1990, 2003]:

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad (5)$$

Only the short type of fibre was used (Dramix 65/35), limited by the 45 mm gap of the concentric BML viscometer at NTNU/Department of Structural Engineering. During trial mixing the rheological properties were evaluated visually (flow, bleeding etc) before measurements of slump flow, T500 (sec), τ_0 and μ. Some initial trial mixes without fibre and some efforts to increase the fibre content from 1.5 to 4.5 % of aggregate volume were made. These are not included in table 5 because flow-able properties were not obtained. Here we only show rheological measurements of those mixes that were successful in terms of obtaining realistic slump flow- and T500 values. The problems with the unsuccessful fibre mixes were those usually encountered at too high fibre contents; absence of flow due to fibre interaction. Clearly there is no way to proportion fibre reinforced concrete without trial mixing, visual inspection and measurements of the basic fresh properties slump flow time (s) and slump flow (mm) according to guidelines such as [European SCC guide 2005, Norwegian Concr Ass 2007].

Figures 4 and 5 show fresh properties vs. aggregate-void saturation. In general increased aggregate-void saturation ratio showed very good relation to improved rheology in terms of increased slump flow and reduced plastic viscosity and similarly for reduced yield and T500 at increasing aggregate void saturation trend though with lower correlation. Plotting the excess phase volumes above void saturation in litres versus rheological property did not show such clear relations. We also emphasize that these statements are mainly indicative due to the low number of mixes. It could also be that the correlation to yield is better than indicated by figure 4 since slump flow also shown in figure 4 correlates to yield (plot not shown). Furthermore, not all the flowing mixes obtained self compacting properties as indicated by T500 values of up to 5 seconds and slump flow values below 550 mm [EU SCC guide 2005]. It is tempting to say that the fibres have simply reduced the packing. Furthermore, as long as we can lubricate by an appropriate excess paste volume, which probably is expressed by the aggregate void saturation ratio, we can predict rheology from the latter parameter. However, the relation might not be as general as indicated in this study. From the review on how fibres affect the rheology of suspensions [Björkman 2008a,b] it is known that the size of the sphere projected by rotating the fibres around their centres will describe the probability of fibre interaction or fibre-fibre impact during flow. Some purely mathematical models have been made and tested describing the relationship between particle content and rheology [Geiker et al 2002] and also for fibres [Bui et al 2003] applying equivalent thickness. The aggregate-void saturation ratio is however easier to quantify. Presently we do not fully understand why C measured on packed particles relates to properties of the same particles when dispersed in a lubricating phase and this needs to be further investigated. It is often found that specific surface and packing relate [Cumberland & Crawford 1987, Smeplass pers comm]. This is probably part of the explanation for that angularity and specific surface, and consequently equivalent thickness of paste layer relate to packing. However, the distinction between equivalent paste or matrix layer thickness around particles on one hand, and the excess paste between these covered particles is not clear. Thus we still are left with a physical problem of determining how large fraction of the void filling that is contributing to the flow properties and how large fraction that is adhering to surfaces, contributing perhaps more to spacing and less to lubrication.

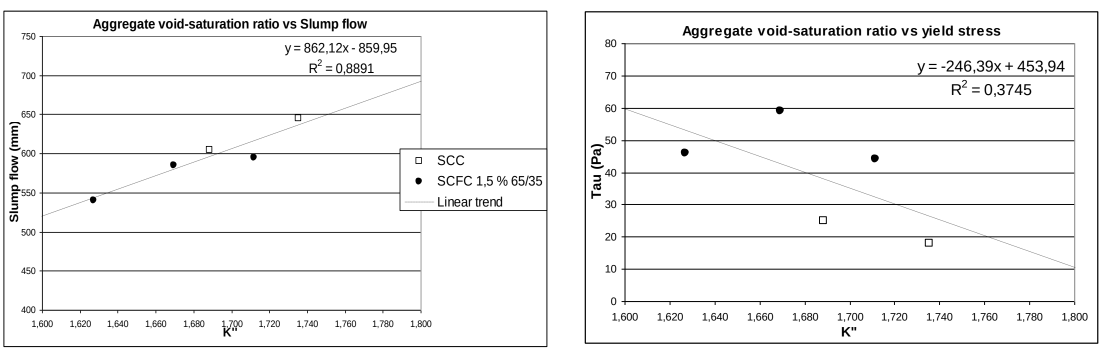

Fig. 4. Slump Flow and Yield Stress vs K'' = $(V_m - V_{air})/(1 - C_{>0.125})$

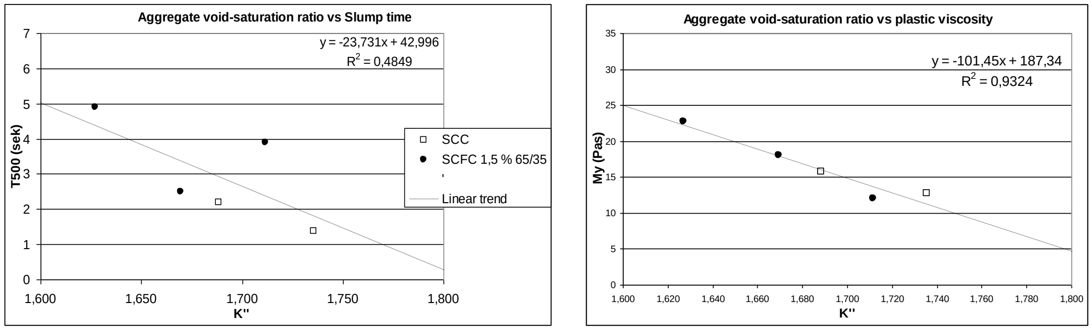

Fig. 5. Slump-flow Time and Plastic Viscosity vs K'' = $(V_m - V_{air})/(1 - C_{>0.125})$

Clearly more basic research within this topic is needed. An immediate investigation that could be done with the present data is to study whether the relation between aggregate-void saturation and rheological data is improved by calculating the packing of different sizes for distinction between particles and lubricating phase. This could for example be particles > 0.063 mm versus matrix < 0.063mm, or all aggregates and binder particles versus only liquids as lubricant phases.

CONCLUSION

The ratio between volume of lubricating phase (paste, matrix) and void space between loose particles, termed the aggregate-void saturation ratio, can be used for proportioning fibre reinforced concrete. The utility of this parameter was established for fibre concrete by determining the packing of aggregate and aggregate-fibre mixes and then varying the volume of lubricating matrix phase. Rheological measurements on the resulting concretes with highly flow-able consistencies showed relations between aggregate void saturation and rheological parameters such as plastic viscosity and slump-flow.

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