Practical Test Methods for Concrete Rheology Evaluation

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1 Introduction

Fresh rheoplastic concrete usually is characterized on the job site with standardised methods such as slump, DIN Flow or VEBE Test . The obtained values are used to describe the initial fluidity of the concrete and the workability retention. Nevertheless, these methods very often fail in characterizing rheologic properties of a concrete which can be depicted with many different terms e.g. wet , stiff, viscous, gummy, cohesive, good, poor.
Especially the use of polycarboxylate superplasticizers, which allow the production of highly fluid concretes with very low water to cement ratios, often results in a cohesive concrete. Up to now, cohesiveness has been considered a qualitative feeling, a subjective impression of the person working with the concrete. Due to its subjective nature and the lack of objective measurement methods, a precise definition of cohesiveness can't be given so far.
In the last years more and more effort was made in characterizing the rheologic properties of concrete [1,2] mainly by using specially designed rheometers. Nevertheless rheometers remain instruments for concrete research and the interpretation of rheologic parameters with respect to specific practical behaviour such as concrete placing and finishing easiness has not been completely clarified yet.
In this work, some methods are presented which were developed with the aim to characterize the feeling of cohesiveness in a quantitative or semi-quantitative way. Special effort was made in investigating methods which are a) correlated with practical behaviour of mortar/concrete such as placing and finishing, b) fast, c) can be applied easily with a considerable low amount of material in the lab and in the field and d) are not cost-intensive. A correlation with results obtained by rheologic evaluation with rheometers is also reported .

2 Theoretical considerations

The rheology of rheoplastic concrete can be described with good accuracy according to the Bingham theory and therefore two rheologic parameters are of interest: the yield stress value τ_0 and the plastic viscosity μ. They can be measured with specially designed rheometers like the BML [3] or the IBB rheometer [4], BTRHEOM, Two-point by Tattersal and Bloomer . Two studies performed at the National Institute for Standard and Technologies (NIST) have shown that the absolute values must be reviewed with caution since very different values were obtained when concrete was evaluated with different rheometers [5,6].

Despite that the absolute values were different, the trends were displayed right.
The influences of different parameters on the yield stress and plastic viscosity is depicted schematically in Figure 1.

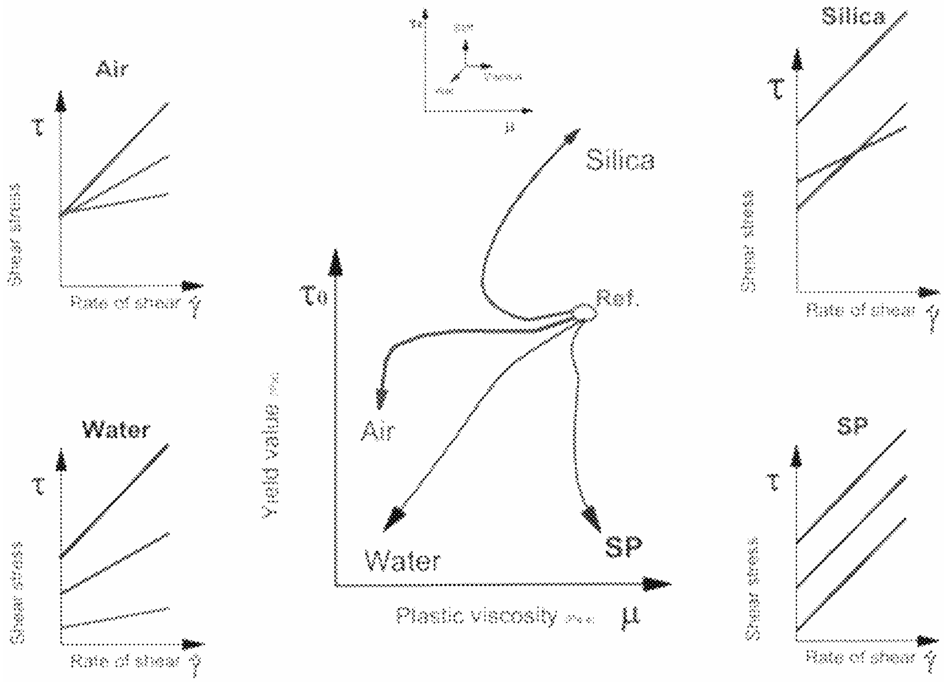

Figure 1: Influence of certain parameters on the yield stress and plastic viscosity of concrete [7]

As can be seen, the addition of superplasticizer reduces the yield stress leaving the plastic viscosity almost unchanged. Recent publications confirm that strong correlation between yield stress and slump value but none between slump value and plastic viscosity. [6,8]
This explains why, with the ongoing usage of high range superplasticizers, the term "cohesiveness" gains importance. This superplasticizers permit to produce high slump concrete at low water/cement ratio, the concrete fulfils the requested parameters but often is very viscous. In the field this is an important issue since a viscous concrete requires more energy to be pumped, to fill the moulds and to be finished.
As already described, cohesiveness is a qualitative and subjective feeling of the concrete worker. Dealing with cohesiveness and finding ways to reduce it therefore requires a quantification method. From the theoretical considerations described above, it seems quite obvious that cohesiveness is related to the plastic viscosity. To clarify this issue, some attempt to set up appropriate measurement methods can be found in literature. The modified slump published by Ferraris and De Larrard in which a rod is put in cone and a metal plate on the top of concrete [9] should permit to predict the cohesiveness by measuring the time the plate needs to drop 10cm. Also a calculation method for

yield stress and plastic viscosity is presented. Nevertheless high standard deviation in comparison with rheometer evaluations could be observed. A detailed overview of 61 methods for workability evaluation is given by Koehler and Fowler [10]. However, as already mentioned, the correlation with the practical application of concrete is still difficult. We therefore see the need for further developing methods to measure cohesiveness at least in a semi-quantitative way "in agreement with the feeling of the users of concrete". It was not our aim to examine precisely *why* one concrete is less cohesive than another (e.g. due to higher air content or better quality) but *how much* less cohesive it is. Therefore we will differentiate between quantitative methods producing scientific values and semi-quantitative methods giving a "number value" to cohesiveness which allows comparing different concretes.

3 Method presentation

3.1 Shock table

Since shock table both for mortar (UNI 7044) and concrete tests (UNI 8020) are standardised and commonly used, it is worth evaluating if it can contribute for a better understanding of cohesiveness.
We investigated in concrete a) if a first indication of cohesiveness can already be given when the cone (top / bottom diameter / height 17 / 27 / 13 cm) is lifted and the flow without shocks is measured (static flow) and b) measuring the flow after 5,10,15 and 20 shocks can give some more indication of cohesiveness.
Table 1 shows an example of a test series evaluating 4 superplastisized concretes under addition of different viscosity modifying agents; in Figure 2 the results of the shock table evaluation are presented.

Table 1: Concrete tests with different viscosity modifying agents (Mix design: Cement I 52,5 R: 490 kg/m^3, Limestone Filler: 15 kg/m^3, Sand: 1100 kg/m^3, Aggregates: 818 kg/m^3, Water: 152 L/m^3), PCE=polycarboxylate ether, VMA1-3: Viscosity modifying agents of different nature

Superplasticizer	Active Dosage /%	Viscosity Modifier	Active Dosage /%	w/c ratio	Slump / cm
PCE	0,24			0,31	25
PCE	0,24	VMA 1	0,06	0,31	24
PCE	0,24	VMA 2	0,30	0,31	24
PCE	0,24	VMA 3	0,06	0,31	25

Despite having similar slump values, the flow without applying shocks can be very different. Considering the obtained flow after 5,10,15 and 20 seconds, the slope of the regression line can give an indication of the cohesiveness. A steeper line means a better response to the force the shocks apply on the concrete and represents therefore a concrete which is easier to move which means less cohesive. This must be considered in combination with the static flow (flow without shocks

applied). A higher static flow exhibits a concrete which collapses better under its own weight and spreads easier. Obviously the flow increment by applying shocks in these cases can be lower.
We consider this method to provide only a very rough comparison of concrete cohesiveness. Notable differences in cohesiveness could only be observed in concretes having a high amount of fines. Evaluating concrete mixes with lower amount of fines, although giving the impression of being different in terms of cohesiveness, the shock table evidenced no more any differences.

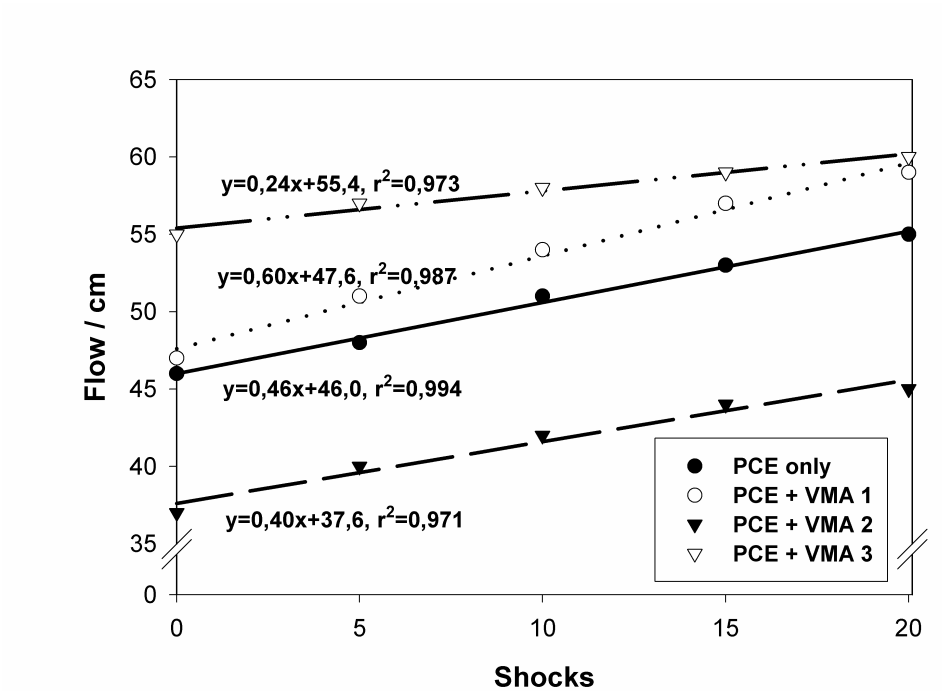

Figure 2: Concrete flow after 0,5,10,15 and 20 shocks, series with a poly-carboxylate ether polymer and different viscosity modifying agents (Mix design see Table 1)

We also explored the applicability of this concept in standard mortar tests. It turns out to be limited to fluid mortars with a dynamic flow value of 120% and above, test results with stiffer mortars deviate too much. Better results could be achieved when the cone used in concrete test was applied.

Applicability / Limits

Very fluid mortars with a high static flow are limited to measure since the shocks applied only have minor influence on the spread and the differences are no more obvious. In concrete tests we only obtained reasonable results when evaluating concretes with high fines content.

3.2 Fill-Box

Picture 1: Fill - Box

As described in Chapter 2, a viscous concrete is hard to place. In respect to our aim of a quantification it was therefore necessary being able to say *how* hard the concrete is to place. For this, the Fill-Box under vibration concept was investigated in terms of "making placement" visible and measurable at least in a semi-quantitative way. The Fill-Box is a transparent box of 50x30x30cm in which each 5 cm vertical bars are implied. The first 15cm are without bars so that the concrete can be introduced (see Picture 1).

10 litres of concrete are poured in the Fill-Box and the profile of the levelled concrete is taken. This profile is considered to be an indication of the filling ability of a concrete. After that the concrete is vibrated for 20 seconds and again the profile of the concrete was measured. As an example, in Figure 3 the schematic drawing of the concrete profiles revealed from an experiment in which two concretes with equal slump but made with different polymers PCE 1 (Glenium ACE 40) and PCE 2 (Glenium ACE 40 + air entrainer) are shown.

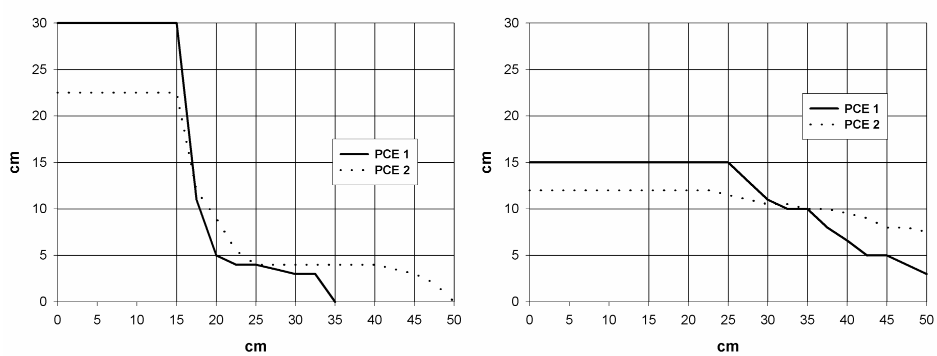

Figure 3: Schematic view of the concrete profile in Fill-Box evaluation, a) initial profile, b) profile after 20s of vibration (Cement II/A-LL 42,5 R: 350 kg/m^3, Sand: 930 kg/m3, Crushed Aggrates: 950 kg/m^3, Water: 171 L/m^3 (w/c ratio: 0,49), Polymer dosage: 2,46 L/m^3 (active dosage: 0,21%), Initial slump values both 22cm, PCE1=Glenium ACE 40, PCE2=Glenium ACE 40 + Air entrainer

Despite the initial slump values are the same, the concrete made with PCE 2 moves more smoothly and can level itself better in the Fill-Box, both before and after vibration. These results are inline with the subjective evaluation that concrete 2 seems to be less cohesive. With this method the cohesiveness of concretes can be compared and it can be quantified, how cohesive one concrete seems to be in comparison to others.

Applicability / Limits

We obtained good results in measuring fluid concretes with a slump value in the range of 18 to 24 cm. Maximum aggregate size is 25mm, otherwise the levelling of the concrete will be influenced. Special care must be taken to have a concrete with reasonable workability retention for the time period in which the test is performed. For precisely comparing two concretes, the initial slump values have to be equal.

3. 3 The dynamometer

When a worker evaluates the cohesiveness with a trowel, he applies a certain force and then, with his experience, evaluates the response of the concrete being more or less cohesive. Since this is a very subjective and unsatisfactory method, we looked out for a more precise solution to a) simulate this procedure and b) quantify the cohesiveness.

Picture 2: Dynamometer

Therefore we set-up in our laboratories the application of a dynamometer (see Picture 2) which measures the force necessary inserting and moving a probe into the cementitious suspension. Since the aggregates in concrete may disturb the measurement, we concentrated on evaluating in mortar and in mortar obtained by sieving concrete (maximum diameter as passing the sieve 2 mm). In all tests, a round plate (diameter 50mm) as probe head proved to be most suitable. A probehead speed of 0,8 cm $\cdot s^{-1}$ showed to be optimal . At inferior speed, the load recorded was too low due to fast equilibration of the mortar on the probehead pressure. Using higher speeds, stiffer mortar tends to show a load which exceeded the range of the dynamometer. 700g of mortar and sieved concrete respectively were used for evaluation while the probe head is moving down penetrating the mortar, the load is registered.

In table 2 an example of a test series is presented in which mortars with different w/c ratio were compared. Polymer dosage was adjusted for reaching equal flow.

Table 2: Mortar tests with different w/c ratio / admixture dosage (Cement I 52,5 R: 900g, Sand: 2700g (Normensand))

Superplasticizer	Active Dosage /%	w/c ratio	Initial Flow / %
Glenium 21	0,24	0,44	110
Glenium 21	0,30	0,41	114
Glenium 21	0,36	0,39	114

Despite the polymers are very similar in terms of their fluidification properties, the mortars obtained exhibits big differences in cohesiveness (see Figure 4).

By lowering the w/c ratio, the dynamometer curves of the mortars results in a steeper load/penetration depth curve with a higher final load, which represents a mortar which is more difficult to move and therefore more cohesive. As indicated for the third curve, the curve can be divided in three parts . The first part represents the force obtained when the probe head touches the mortar surface and first compresses the mortar. Exceeding a certain value, the mortar starts to move. This movement then is depicted in the second part and is represented by a less steep load/penetration depth curve.

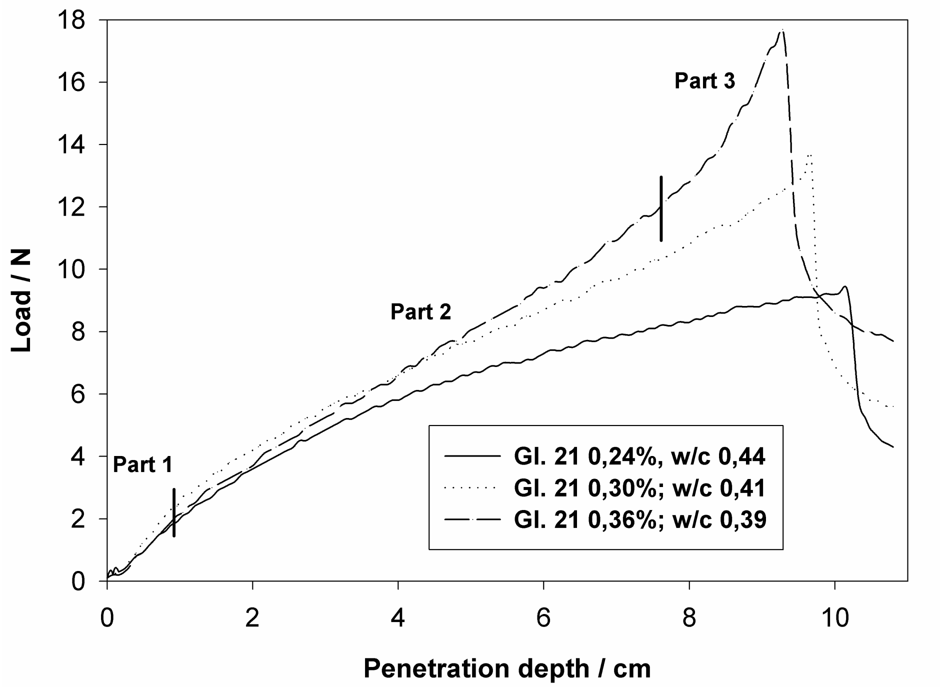

Figure 4: Dynamometer test curves from testing mortars with different admixture dosage and w/c ratio (Mortar details see Table 2, Probe head speed 0,8 cm/sec)

Part three represents the part in which the probe head moves close to the bottom and additional compression of the remaining mortar can be observed. As can be seen in Figure 4, this division into parts gets more obvious when evaluating cohesive mortars. Equivalent results could be observed in evaluation of sieved concrete (passing 2mm sieve).

Applicability / Limits

We found a good applicability of this method using mortar and sieved concrete. In mortar, a dynamic flow range of 80 – 120% proved to be optimal, below this the mortar will be too stiff to move, above the differences observable are in the range of the detection limit of the instrument. Staying in this range of mortar properties, repeatability is generally good. Care must be taken that during the measurement the mortar does not loose workability.

4 Comparison of the methods with rheologic investigations

To verify the results obtained by the methods developed and described above, rheologic investigations by means of rheometers can be useful. Since the shock table method proved to be limited, strong effort was laid in the Fill-Box and the dynamometer methods. In the following, examples of simultaneous evaluations are presented.

4.1 Comparison Fill-Box – BML Rheometer evaluation

The test series presented in chapter 3.2 was repeated and the concrete investigated with the BML rheometer. Best reproducible results could be obtained by applying a stepwise declining speed curve (maximum/minimum rotational speed 0,4/0,08 s^{-1}) and a concrete volume of 14-15 Litres. The results are depicted in Table 3.

Table 3: Concrete evaluation with BML rheometer (Cement II/A -LL 42,5 R: 350 kg/m^3, Sand: 940 kg/m3, Round Aggrates: 980 kg/m^3, Water: 154 L/m^3, Polymer dosage 1,87 L/m^3 (30% solution)), t_o = yield stress, m = plastic viscosity, PCE1=Glenium ACE 40, PCE2=Glenium ACE 40 + Air entrainer

Superplasticizer	Active Dosage /%	W/C ratio	Slump / cm	t_o / Pa	m / Pas
PCE 1	0,16	0,44	20,0	234	140
PCE 2	0,16	0,44	19,5	244	95

In accordance with the theory [8], τ_0 correlates to the slump value. PCE 2 exhibits a significantly lower plastic viscosity. In correlation with the Fill-Box experiment, this proves the results that the concrete made with PCE 2 is less cohesive.
Generally we observed good concordance of the cohesiveness trends observed in Fill-Box and BML rheometer evaluation. Using the BML rheometer, the aggregate size is limited to 16mm.

4.2 Comparison Dynamometer – Viskomat NT evaluation

Since for the dynamometer evaluation only mortar or sieved concrete can be used, it is obvious to verify the results obtained by evaluation of the rheologic properties using a Viskomat NT (Schleibinger Geraete [11]). Best results could be obtained by applying a stepwise declining speed curve (maximum/minimum rotational speed 2,67/0,17 s^{-1}, total ramp time 3min). At each rotational speed step, 10 measurement points were taken and their average value used for further calculation.
Picking up the test series described in section 3.3 the results obtained from the Viskomat NT evaluation are displayed in Figure 5.

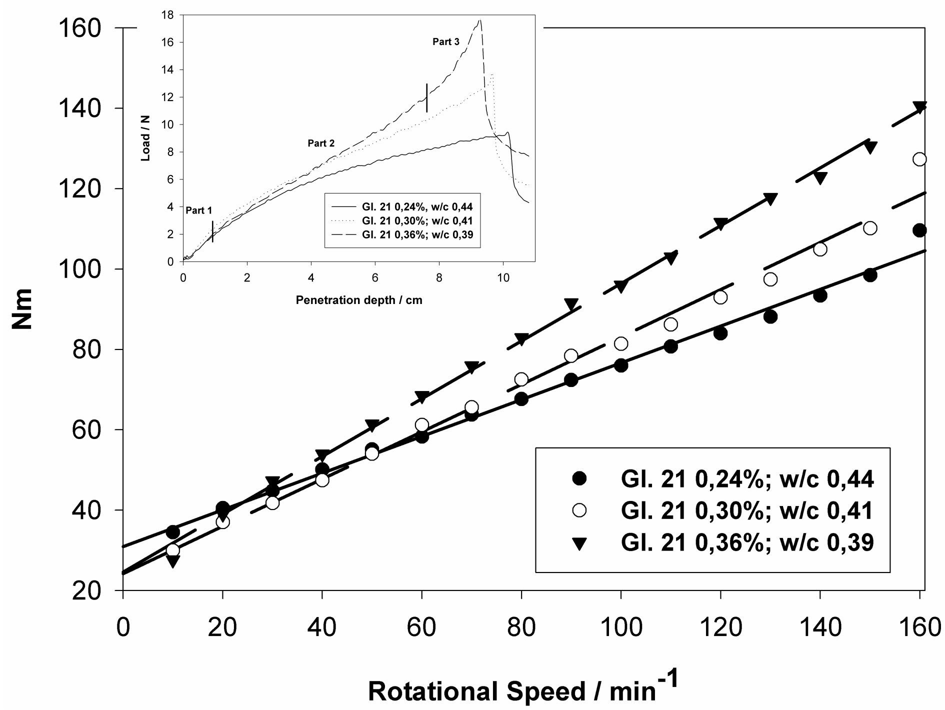

Figure 5: Results from the mortar (equal flow but different w/c ratio and polymer dosage, see section 3.3, and table 2) e valuation with V iskomat NT. Upper left corner dy namometer curves

Mortars with lowe r w/c ratio and higher admixture dosage exhibit a steeper curve and therefore a higher plastic viscosity. This is in line with the dynamometer evaluation revealing also th is trend of cohesiveness.

As another example, the correlation between dynamometer and Viskomat evaluation using mortars with different air volumes is displayed in Table 4 and Figure 6.

Table 4: Mortar tests with different w/c ratio / admixture dosage (Cement I 52,5 R: 900g, Sand: 2700g (Normensand)) , PCE1=Glenium ACE 40, PCE2=Glenium ACE 40 + Air entrainer

Superplasticizer	Active Dosage / %	W/C Ratio	Initial Flow / %	Airv olume / %
PCE 1	0,24	0,42	115	4,9%
PCE 2	0,22	0,42	110	7,2%

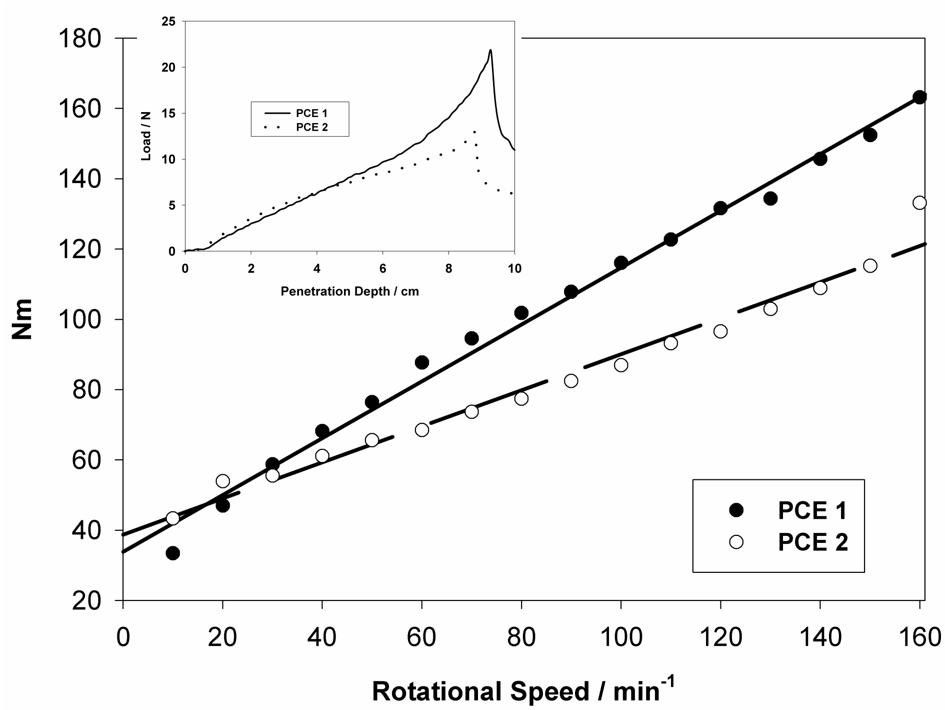

Figure 6: Mortar test evaluation with Viskomat N T (large diagram) a nd dynamometer (small diagram) , Mortar details see Table 4.

The higher amount of air in mortar 2 is displayed right by the Viskomat NT by having a lower plastic viscosity. This is represented in the dynamometer diagram with a lower fina l load and a less st eep load/penetration depth curve. The trend displayed with b oth evaluation methods is obvious, exhibiting the mortar with PCE 2 less coh esive than the mortar in which PCE 1 was used.

5 Summary / Conclusion

Cohesiveness of rheoplastic concrete is getting more and more important on the job -site. Dealing with this parameter requires reliable methods for a quantification of this value. Parameters such as viscosity and yield value can b e of great help in evaluating some specific rheologic features, but not always easiness of placing and finishing can be correlated to them. In this work, several easier to app ly concrete test methods were presented and evaluated accord ing to their applicability for cohesiveness evaluation. They were compared with rheometric evaluations.

In Table 5 an overview of the methods and their charact eristics are presented.

Table 5: Overview of the evaluation methods and their main characteristics concerning cohesiveness evaluation

	Shock Table	Fill-Box	Dynanometer	Viskomat
Job site application	Possible	Possible	Limited	Limited
Difficulty	Low	Low	Medium	High
Reproducibility	Medium	High	High	High
Sensibility	Low	Medium	Medium	High
Comparison with Trowel feeling	Low	High	High	High

The shock table proved to be very limited in cohesiveness evaluation. Notable differences can only be observed in concretes with a high amount of fines. Therefore, only a rough idea, if at all, of the cohesiveness can be retrieved.

The Fill-Box method showed to be very useful in cohesiveness evaluation of fluid concretes with slump values of 18 cm and above. Showing also good comparison to the feeling the worker has when moving the concrete with the trowel, the Fill-Box can be applied very well for semi-quantitative cohesiveness evaluation.

The more scientific approach using a dynamometer and measuring the force on a probe head while penetrating into mortar or sieved concrete also provides an adequate tool for cohesiveness evaluation. Good concordance with rheometric evaluation using the Viskomat NT can be observed.

All methods presented are limited to application in fluid concretes or mortars. Except the shock table, they can be very useful in concrete cohesiveness evaluation permitting to distinguish concretes in a more precise way than with the subjective test by moving the concrete with a trowel. Despite that they can be used on the job site more easily than rheometers, they do not provide scientific values but they fulfil the aim of a semi-quantitative analysis of concrete cohesiveness in agreement with the “feeling” of the worker.

6 References

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