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Feasibility of Using a Concrete Mixing Truck as a Rheometer (Orlando, Florida)

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Technology Administration, U.S. Department of Commerce

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Participants in the tests at the Cemex Lockhart Plant, Apopka, Florida



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Foreword

The measurement of the properties of fresh concrete at the construction site has been done for the past 100 years using the slump cone test (ASTM C143). With the event of new concrete such as self compacting concrete, it has been generally determined that the slump cone test is not sufficient to qualify the workability of fresh concrete flow. Although many tests [1] have been designed to fully characterize concrete, few are consistently used in the field. The most fundamental are the tests based on rheology (e.g., rotational rheometers) [2, 3]. There is a need for a relatively simple test that could be used in the field but that will fully characterize fresh concrete flow properties.

The goal of the tests reported here was to further determine the feasibility of using a concrete mixing truck as a rotational rheometer. This work is the continuation of preliminary tests [4, 5] that seemed to indicated that the yield stress and the plastic viscosity could be deduced from the measurements of speed and hydraulic pressure performed on a concrete mixing truck. The methodology used is based on using the concrete mixing truck drum rotation rate combined with the measurement of the torque induced by the concrete load. This is similar to the typical method of determining the flow behavior in a traditional rotational rheometer, i.e., the Bingham model: the shear rate (or drum rotational speed) versus the shear stress (or torque) was plotted. The slope of the linear relationship would be the plastic viscosity and the intercept at zero shear rate would be the yield stress.

This report summarizes the material and experiments conducted during 3 days in Orlando, Florida in December 2007. The results are presented and discussed. The results of these experiments are discussed and compared with data provided by an IBB rheometer [14].

These results confirm the conclusion obtained by Amziane et al. [4] that stated that the concrete mixing truck could be used to determine yield stress and correlates well with the slump cone test. Although the relationship between torque and speed was found to be linear, the slope is not correlated to the plastic viscosity as measured by the rheometer. Suggestions are given on how to improve the concrete mixing truck for use as a rheometer but it is not certain that these would solve the problem. Discussion of these conclusions is offered as well how to improve the system.

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1. Introduction

Workability is defined by American Concrete Institute (ACI) 116 [6] as the "ease with which concrete can be mixed, placed, consolidated, and finished to a homogenous condition". This definition is usually translated by a measurement using the slump cone test (ASTM C143 [7]). Recently, the use of special concrete such as self compacting concrete (SCC) has pushed practitioners and researchers to look for other test methods more suitable for capturing the properties of fresh concrete. ACI 238, "Workability of Fresh Concrete", has just recently approved a report including a synthesis of more than 61 existing test methods. This report was largely based on the work by Koehler [1]. The report was recently approved by ACI for publication and it is under press.

It is generally agreed that to completely describe the workability or flow of concrete, one parameter is not enough and therefore a more sophisticated device than the slump cone is needed. The most common approach is to describe the flow of concrete using the Bingham model (equation 1). This model uses two parameters, yield stress, and plastic viscosity, to define flow as a relationship between shear rate and shear stress.

$$\tau = \tau_0 + \mu \dot{\gamma}$$
 [1]

where μ : plastic viscosity

 τ_{o} : yield stress $\dot{\gamma}$: shear rate τ : shear stress

The measurement of the two parameters, yield stress and plastic viscosity, is currently possible only by using a rheometer adapted to concrete [2, 3, 8]. Unfortunately, the current cost of these devices (even if very low compared to the cost of a concrete mixing truck) and their complexities, as compared to the slump test, have restricted the use of rheological measurements mainly to research laboratories.

Examining the rotational rheometers, it can be inferred that they mostly operate under the following equation:

$$T = Y + VN$$
 [2]

where T: Torque $(N \cdot m)$

N: rotation speed (rad/s)

Y: yield value related to the material yield stress $(N \cdot m)$

V: plastic viscosity value related to the material plastic viscosity (N·m·s)

A concrete mixing truck is also a device that turns at various speeds and where the torque could be measured, and using an equation similar to equation 2 would give the yield value and the plastic viscosity value. This is not a totally novel idea [9,10,11] and a state of the art report on this topic was prepared by Amziane et al. [5]. Nevertheless, few studies exist on the prospect of determining the flow properties of the material in a concrete mixing truck in transit to a jobsite [4,12]. Both studies were based on a very limited number of concrete measurements.

The present study includes 21 concrete mixtures made using one concrete mixing truck. The range of plastic viscosity and yield stress was varied by incremental addition of either water or chemical admixtures. Therefore, this study should be able to further determine the validity of the approach and whether measurements with the concrete mixing truck are sensitive enough to capture rheological changes due to composition changes in the concrete mixture.

2. Materials used

2.1. Raw materials

All mixes were produced with the same cement Type I. All mixtures with the exclusion of Mixture A had also an addition of fly ash. The cement composition is shown in Table 1. The fly ash appears to be predominantly amorphous with some quartz, hematite and magnetite from X-ray diffraction (XRD) measurements. The particle size distribution for both materials is shown in Figure 1. It seems that from the sample provided the cement is finer than the fly ash.

Three types of aggregates were used: sand, coarse aggregate and a 3/8 aggregate. Figure 2 shows the distribution measured from aggregates collected at the site.

Phase	Mass fraction [%]
C ₃ S alite	55.6 ± 1.9
C ₂ S belite	26.0 ± 1.3
C ₄ AF ferrite	7.0 ± 1.9
C ₃ Ac	4.9 ± 0.3
C ₃ Ao	1.7 ± 0.7
Anhydride	0.3 ± 0.2
Bassmite	2.8 ± 0.7
Gypsum	0.6 ± 0.0

Table 1: Composition of the cement as measured at NIST by XRD. The standard
deviation is from three replicates.







Figure 2: Size distribution of the aggregates used. A) fine aggregates; B) coarse and nominally 3/8-aggregate

The chemical admixtures used were¹:

- Lignin/polymer blend based water reducer (WRA). All mixtures with the exception of the SCC (or mixture F) contained WRA.
- Two high range water reducers (HRWRA), Poly-carboxylate-based were used: HRWRA A for mixtures C and E; HRWRA B for the SCC (Mixture F).
- A viscosity modifier (VMA) was used for mixtures D and F

2.2. Mixtures design

In planning the mixtures it was decided not to prepare for each test a new batch from raw material, but instead to have three baseline mixtures and to incrementally add in materials (chemical admixtures or water) to change the properties. This is not a perfect method but it allows for the use of one concrete mixing truck to obtain multiple results faster. This procedure would limit the amount of concrete produced and that would need to be disposed after the test.

The three baseline mixtures adopted are:

- 1. Concrete using portland cement
- 2. Concrete using cement with fly ash
- 3. SCC mixture (more cement and more fines)

The baseline mixtures were then used to add materials as shown below

- o Baseline 1: addition of water (in two increments)
- Baseline 2:
 - Addition of water (in two increments)

¹ The admixtures were provided by WR Grace and were commercially available: WRDA 60; the HRWRA were ADVA 140 and ADVA 380; the VMA was V-Mar3.

- Addition of HRWRA (in two increments)
- Addition of VMA (in two increments)
- Baseline 3: Addition of HRWRA and then VMA.

Using the above plan, the mixes prepared are outlined in Table 2. The amount used for each mixture is shown in Table 3. Each new batch is designated by a letter, A to F. The #1 are the baseline mixes and the subsequent numbers are the baseline mixes with additions as outlined in Table 2.

Table 2:	Modification	of the baseline	mixtures a	nd parameter	calculations.	CM is
cementit	ious material (cement + fly as	sh)			

Mixture code	Modifications	Water/CM Mass fraction	Sand /Aggregates Mass Fraction
A1	Baseline 1	0.367	0.437
A2	+76 L of water to A1	0.401	0.437
A3	+170 L of water to A2	0.476	0.437
A4	+76 L of water to A3	0.510	0.437
B1	Baseline 2	0.373	0.438
B2	+76 L of water to B1	0.406	0.438
B3	+ 57 L of water to B2	0.432	0.438
B4	+57 L of water to B3	0.457	0.438
C1	Baseline 2	0.414	0.441
C2	+ 4.7 L of HRWRA to C1	0.414	0.441
C3	+ 7.1 L of HRWRA to C2	0.414	0.441
D1	Baseline 2	0.351	0.448
D2	+ 114 L of water to D1	0.400	0.448
D3	+2.4 L of VMA to D2	0.400	0.448
D4	+2.4 L of VMA to D3	0.400	0.448
E1	Baseline (repeat of C)	0.409	0.444
E2	+ 4.7 L of HRWRA to E1	0.409	0.444
E3	+ 7.1 L of HRWRA to E2	0.409	0.444
F1	Baseline SCC	0.273	0.510
F2	+ 1.6 L of VMA to F1	0.273	0.510
F3	+ 13 L of HRWRA for SCC to F2	0.273	0.510

Mixture code	Cement	FA	Water	1" Aggr.	sand	3/8" Aggr.	WRA	VMA	HRWRA
	kg	kg	L	kg	kg	kg	L	L	L
A1	2258		829	8072	6270		4.4		
A2	2258		905	8072	6270		4.4		
A3	2258		1075	8072	6270		4.4		
A4	2258		1151	8072	6270		4.4		
B1	1805	458	844	7900	6161		3.9		
B2	1805	458	920	7900	6161		3.9		
B3	1805	458	977	7900	6161		3.9		
B4	1805	458	1033	7900	6161		3.9		
C1	1798	448	931	7891	6215		3.9		
C2	1798	448	931	7891	6215		3.9		4.7
C3	1798	448	931	7891	6215		3.9		11.8
D1	1855	444	806	8036	6514		3.9		
D2	1855	444	920	8036	6514		3.9		
D3	1855	444	920	8036	6514		3.9	2.4	
D4	1855	444	920	8036	6514		3.9	4.7	
E1	1801	451	920	7900	6315		3.9		
E2	1801	451	920	7900	6315		8.6		4.7
E3	1801	451	920	7900	6315		15.7		11.8
F1	2446	908	916	2292	6686	4140			
F2	2446	908	916	2292	6686	4140		1.6	
F3	2446	908	916	2292	6686	4140		1.6	13*

Table 3: Mixtures composition. All trucks were initially loaded with 7.6 m³ (10 yd³)of concrete

Note: * The HRWRA used for Mixture F is not the same as the one used for mixtures C and E. It is a special HRWRA specifically designed for SCC.

3. Equipment used

3.1. Rheometer

This apparatus is an instrumented and automated version of the existing apparatus (MKIII) developed by Tattersall [13]. It was modified in Canada by Beaupré [14] to study the behavior of high performance wet-process shotcrete. The basis of the instrument is an impeller, shaped as an H (Figure 3), rotated in increasing and decreasing speeds in the container full of concrete. The torque generated by the resistance of the concrete is measured and recorded. The slope of the torque vs. the rotational speed graph is the plastic viscosity value H and the intercept at zero speed is the yield value G. The apparatus is controlled by a computer and the data are recorded automatically.

This apparatus can be used to test concrete with slumps ranging from 40 mm to 300 mm. The general view of the apparatus is shown in Figure 4. The recommended maximum size aggregate is 25 mm. The sample size is 21 L.



Figure 3: Impeller of the rheometer



Figure 4: Picture of IBB Rheometer

3.2. Instrumented Concrete mixing Truck

The concrete truck geometry was considered typical and a description and analysis could be found in Ref. [4]. The concrete mixing truck needed to be equipped with a system that would allow the measurement of the rotational speed of the mixing drum and the torque resulting from the material in the concrete mixing drum. The procedure to use these measurements for comparison with the rheometer data consisted in rotating the mixing drum at various speeds while the torque was recorded at each speed. The slope of the torque vs. the speed the H or related to the plastic viscosity value and the intercept is G or the yield value. This procedure was similar as used in the rheometer.

The system that was installed in the concrete mixing truck used is a proprietary device that consists in gauges to measure the hydraulic pressure of the oil in the motor that rotates the drum and the speed of rotation of the drum. The system can record both values and make decisions such as addition of water or chemical admixtures to obtain a concrete with the desired characteristics. Each concrete mixing truck equipped with the device needs to be calibrated in order to correlate the oil pressure with the slump measurement. The computerized system also takes into account factors like load size, load age, location and concrete mixing truck motion, which are analyzed by a central microprocessor to determine the slump.

In this study, the drum was rotated at increasing speeds of 0.3 rad/s, 0.6 rad/s, 1.04 rad/s, and 1.5 rad/s (3 rpm, 6 rpm, 10 rpm, and 14 rpm) and the hydraulic pressure was measured at each speed after few minutes or when the pressure was stable. It was important to progress rapidly thru the following steps. The product being tested changes over time due to chemical interactions and these changes need to be minimized to achieve the most accurate results. The basic procedure was:

- Fully load a concrete mixing truck with a product that has a relatively low initial slump.
- Capture sensor readings at 0.31 rad/s, 0.62 rad/s, 1/05 rad/s and 1.47 rad/s (3 rpm, 6 rpm, 10 rpm, and 14 rpm) rotational speed of the drum.
- Discharge a small amount of material for testing with a cone, rheometer, and etc.
- Add a liquid component to modify the rheological properties.
- Properly mix the load.
- Then repeat these steps starting with the capture of sensor readings at each of the drum speeds.

This sequence is continued until an hour has elapsed or the material has been modified outside of its commercially useful condition.

3.3. Location

All tests were performed in one location at a ready-mixed concrete facility. The facility had a production size automated batch plant. It included silos for aggregates, cement, and fly ash and containers for the various chemical admixtures (Figure 5). The aggregates were stored outside and then transferred into a batch silo before being used for the mixtures.

All mixture materials were added directly to the concrete mixing truck and mixed in the concrete mixing truck. The same concrete mixing truck was used for all the tests.

All mixtures were mixed in the concrete mixing truck while the slump meter was monitored. Water was adjusted to obtain the desirable baseline mixture. A wheel barrow full was discharged from the concrete mixing truck for testing and the concrete mixing truck was returned to the mixing routine. Materials were added as described in Table 2. After each addition, material was discharged for testing. Once all tests and additions were completed, the material was disposed off.



Figure 5: View of the batch plant

3.4. Other tests

3.4.1. Fresh concrete testing

Standard tests were also performed to ensure that the concrete produced was of desired quality. The tests are listed below and the results obtained are in Table 4:

- Slump test for mixture A to E and the slump flow for mixture F. This test was measured twice using two slump cones. The average is reported.
- Air content using a pressure meter (ASTM C 231)
- Density using the unit weight method. The container was 7 L (0.247 ft³) and the tare mass of the container was 3.5 kg (7.5 lb).

The temperature of the concrete was measured both at discharge in the wheel barrow (labeled *Barrel* in Table 4) and in the rheometer (labeled *Rheom*. in Table 4).

Mixture code	Slump		Slump		Air content by	Density or Unit weight	Tempe	erature+
			pressure		Barrel	Rheom.		
	in	mm	%	kg/m ³	°C	°C		
A1	2.0	51	1.6	2295	23.4	23.4		
A2	3.5	89	1.5	2289	23.5	23.9		
A3	7.3	184	1.0	2276	25.0	25.0		
A4	7.1	181	1.9	2259	25.4	25.2		
B1	5.3	133	0.2	2256	23.5	23.7		
B2	7.0	178	0.2	2301	24.9	24.9		
B3	7.6	194	0.0	2305	25.2	25.1		
B4	8.0	203	0.0	2253	25.5	25.1		
C1*	6.4	162	0.4	2318	22.4	22.4		
C2	7.0	178	0.6	2314	22.4	22.4		
C3	9.4	238	0.6	2311	23.1	23.1		
D1	3.9	98	0.4	2314	26.1	26.2		
D2	6.5	165	0.2	2301	26.3	26.2		
D3	5.8	146	0.3	2298	25.4	25.7		
D4	4.4	111	0.4	2305	27.2	27.3		
E1	4.4	111	0.6	2314	24.1	24.1		
E2	6.0	152	1.0	2315	24.6	24.9		
E3	8.0	203	1.2	2318	25.3	25.2		
F1	4.5	114		1.1	24.9	24.9		
F2	3.9	98		1.1	25.4	25.4		
F3#	31.0	787		0.4	25.7	25.5		

Table 4: Other tests performed.

Notes: * Strong segregation was observed (Figure 6)

Slump flow was measured instead of slump as this is a SCC mixture.

+ Temperature of the wheel barrel (labeled *Barrel*) and of the rheometer (labeled *Rheom*.)



Figure 6: Mixture C and the very apparent segregation. The segregation was probably due to an error in batching leading to higher content in coarse aggregates and less sand. This could have being caused by inappropriate accounting for the moisture content of the aggregates.

3.4.2. Compressive strength tests

Cylinders were cast of all baseline mixtures for testing compressive strength at 3 d (1 cylinder), 7 d (2 cylinders), and 28 d (2 cylinders). The results are shown on Table 5.

The trends are that for mixtures A and B, compressive strength decreases from A1 to A4 and from B1 to B4, respectively. This is expected as these mixtures were modified by addition of water. Mixture C shows no significant change in strength from C1 to C3. Again the results are as expected as the mixture was modified by the addition of HRWRA and no water.

These results are given for information only, as the main scope of the report was to compare the fresh properties of the concrete by using two methods.

Mixture	3 Days 7 Days [MPa]			28 Days [MPa]					
code	[MPa]	Cyl#1	Cyl#2	Average	St. Dev.	Cyl#1	Cyl#2	Average	St. Dev.
A1	21.1	29.4	28.8	29.1	0.4	41.8	41.2	41.5	0.4
A2	17.9	26.7	26.3	26.5	0.3	39.6	39.6	39.6	0.0
A3	15.0	22.9	21.9	22.4	0.7	32.5	34.5	33.5	1.4
A4	12.8	18.7	20.5	19.6	1.3	31.9	30.6	31.3	0.9
B1	12.3	19.5	18.9	19.2	0.4	33.4	33.3	33.3	0.0
B2	11.3	17.3	17.3	17.3	0.0	31.6	32.3	32.0	0.5
B3	10.4	15.7	15.5	15.6	0.1	30.1	29.0	29.6	0.8
B4	10.0	14.7	14.8	14.8	0.1	28.6	27.9	28.3	0.5
C1*	12.1	19.9	18.8	19.3	0.8	34.5	33.7	34.1	0.6
C2	12.0	19.6	18.5	19.1	0.7	34.1	34.9	34.5	0.5
C3	13.7	20.6	21.4	21.0	0.5	31.7	33.3	32.5	1.1
D1	11.7	19.5	19.4	19.4	0.1	33.3	35.1	34.2	1.3
D2	10.1	17.0	17.9	17.4	0.7	29.5	30.8	30.2	0.9
D3	10.5	16.5	16.7	16.6	0.1	30.7	30.7	30.7	0.0
D4	11.0	18.4	19.0	18.7	0.4	30.9	30.4	30.6	0.3

 Table 5: Compressive strength results

Note: * Strong segregation was observed (Figure 6)

4. Results

4.1. Calculation of yield stress and plastic viscosity

4.1.1. Concrete mixing truck data

To turn the drum of the concrete mixing truck empty, energy is needed and this could be determined by a measurement of the pressure developed in the hydraulic system of the concrete mixing truck. But the portion of the pressure that is of interest is the pressure due to the concrete in the concrete mixing truck, not the pressure needed to turn the empty concrete mixing truck. Therefore, the pressure values obtained with the concrete mixing truck filled with concrete need to be offset by the values obtained in an empty concrete mixing truck. Figure 7 shows the pressure obtained at the various rotational speeds. The slope of the linear regression is 1106 kPa·s/rad and the intercept is 2391 kPa. The R^2 of the regression is 0.93. These values should be used to correct the values measured with the concrete mixing truck with concrete.

The following equation could be written:

$$P_T = P_e + P_c = (a + bv) + (G_t + H_t v) = (a + G_t) + (b + H_t)v$$
[3]

Where: P_T = the total pressure measured for the concrete mixing truck with concrete

 P_{e} , P_{c} = the pressure measure with the empty concrete mixing truck and due to the concrete alone, respectively

a, b = constant to describe the pressure and speed relationship

 G_t , H_t = the yield value and the plastic viscosity value according to Bingham of the concrete sheared measured with the concrete mixing truck

v = the rotational speed of the drum

From equation 3, G_t and H_t could be calculated from the measurements of the total pressure, P_T , if the parameters *a* and *b* are known. In our case, the parameters *a* and *b* can be obtained from the data shown in Figure 7 and they are 2391 kPa and 1106 kPa·s/rad respectively. Therefore, in the rest of this report the data with the concrete mixing truck were corrected using equation 1.

A complete measurement error estimation is not possible due to the method used to obtain the data. Nevertheless, the pressure sensor has a 1% error. The rotational speed measurements are estimated to about 1 % as well. However, due to fluctuating speed and pressure of the mixer during the measurement, the error might not be constant. The reported values are obtained by an averaging algorithms calibrated to obtain a slump value within 12.7 mm (0.5 in) of the target slump.

Figure 8 shows using mixture A as an example. The data were obtained by measuring the total pressure versus the rotational speed. The maximum speed used was lower than the one used for the empty concrete mixing truck.



Figure 7: Measurements on the empty concrete mixing truck.



Figure 8: Example of results obtained with the concrete mixing truck measurements. The total pressure, P_T, versus the rotational speed is shown here.

Mixture	Pla	astic viscosity v	Yield value				
Code	From to	tal pressure	H _t	From tota	al pressure	G _t	\mathbf{R}^2
	Psi/rpm	kPa·s/rad	kPa·s/rad	psi	kPa	kPa	
A1	23	1538	433	1839	12679	10288	0.55
A2	49	3215	2110	1040	7172	4781	0.99
A3	48	3163	2057	679	4685	2294	0.99
A4	44	2901	1795	650	4479	2088	0.99
B1	52	3419	2313	1064	7339	4948	0.99
B2	53	3468	2363	799	5507	3116	0.99
B3	50	3284	2178	700	4827	2436	0.99
B4	47	3108	2002	646	4456	2065	0.99
C1	48	3176	2070	1156	7968	5577	0.99
C2	54	3583	2477	800	5519	3128	0.99
C3	53	3504	2399	527	3631	1241	1.00
D1	49	3223	2117	822	5668	3277	0.99
D2	46	3057	1951	922	6359	3968	0.99
D3	50	3268	2162	1004	6924	4533	0.99
E1	43	2804	1698	1427	9837	7446	0.99
E2	47	3122	2017	1033	7125	4734	0.99
E3	51	3353	2247	749	5167	2776	0.98
F1	46	3007	1901	1190	8206	5815	0.99
F2	45	2976	1870	1249	8609	6218	0.99
F3	56	3676	2570	305	2104	-286	0.99

Table 6: Calculated values from the concrete mixing truck measurements.Discussion on measurement error is in the text.

4.1.2. Rheometer data

An example of the type of curves obtained is shown in Figure 9. For each mixture, two measurements were done and Table 7 shows the results obtained. For all mixtures, the standard deviation of the plastic viscosity value and yield value was calculated (Table 7). In two cases, such as mixtures A1 and C2, one of the measurements was not usable due to either segregation (C2) or was not measured (A1). Also, for each mixture the average R^2 , a correlation factor, that indicates how linear the measured curve was is also shown in Table 7. An R^2 value of 1 indicate a perfect linear relationship. Any value below 0.80 indicates that the data do not follow a linear fit very well.

Other models than Bingham could have been examined. For instance, Herschel-Buckley could results in a better fit for some of the rheometer data. On the other hand the truck data have a R^2 of 0.99 in most case denoting a linear behavior. Using two different models for the two systems would have rendered the comparison for the plastic viscosity between the two devices almost impossible. Therefore, it was decided to limit the analysis to the most simple and most common model, i.e., the Bingham model.

This decision led to negative yield stresses values for mixture C, D2 and F3, because these values are not the real yield stress but an extrapolation to zero shear rate (or

rotational speed) of the torque-speed curve [15]. Mixture C data should be discarded because of the severe segregation due to an error in batching (Figure 6). In the case of D2 and F3 the standard deviation on the measurements is of the same order of magnitude as the value itself. Therefore, other sources of errors are involved.



Figure 9: Example of data from Mixture A obtained with the rheometer.

4.2. Comparison of yield stress and slump

The yield stress is shown in Figure 10 plotted versus the yield stress as calculated either using the concrete mixing truck data or the rheometer data. It is clear from Figure 10 that a linear correlation exists between the slump and the yield stress as measured either by the concrete mixing truck and the rheometer. The correlation coefficient is -0.84 for the concrete mixing truck data and -0.88 for the rheometer data. The negative correlation is due to the fact that the slump is increasing when the yield stress is decreasing.

These results are as expected both for the concrete mixing truck and for the rheometer. The pressure from the concrete mixing truck has been used for years as an approximation of the slump value. A correlation can also be determined for a concrete mixing truck to predict the slump from the pressure measurements at one speed. Also, the correlation between the Bingham yield value and slump has been shown to exist in the literature [2, 3, 8, 16].

Mixture	Plastic v	iscosity	Yield			
	value	, H _R	G	G_R		
Code	Average	Std	Average	Std	\mathbf{R}^2	
	N·m·s	N·m·s	N·m	N·m		
A1	13.3		4.8		0.95	
A2	7.6	0.2	2.8	0.4	0.74	
A3	8.4	1.8	0.3	1.3	0.91	
A4	4.4	0.0	0.4	0.1	0.94	
B1	9.6	1.3	1.1	0.3	0.95	
B2	8.8	2.1	0.0	0.9	0.94	
B3	6.8	0.3	0.3	0.3	0.86	
B4	9.5	1.6	-0.5	0.6	0.77	
C1*	17.80	3.44	-0.88	0.98	0.80	
C2*	16.69		-0.34		0.90	
C3*	9.64	2.38	-1.07	1.53	0.91	
D1	13.0	0.9	1.7	0.1	0.81	
D2	10.4	3.7	-0.3	0.8	0.83	
D3	7.3	2.8	0.8	1.0	0.87	
D4	6.5	0.4	1.7	0.0	0.84	
E1	8.8	0.9	2.9	0.7	0.88	
E2	10.9	4.0	0.9	1.4	0.90	
E3	9.5	2.7	0.4	1.1	0.92	
F1	5.1	0.4	3.9	0.4	0.92	
F2	4.9	0.9	3.9	0.5	0.92	
F3	4.8	0.4	-0.2	0.2	0.97	

 Table 7: Calculated values from the rheometer measurements

Note: * Strong segregation was observed (Figure 6)



Figure 10 : Relationship between slump and yield stress. The circles points are from mixture C1 to C3 that segregated.

4.3. Comparison of results between concrete mixing truck and rheometer

4.3.1. Comparison of rheological value measurements

The yield values as measured from the concrete mixing truck (corrected values) and the rheometer are shown in Figure 11. The correlation between the two values is 0.77 but it becomes 0.85 if the data from C mixtures are not considered due to segregation (Figure 6). This is an acceptable correlation. This is not too surprising, as the concrete mixing truck measurements are designed to measure yield stress.

The plastic viscosity as measured from the concrete mixing truck (corrected values) and the rheometer are shown in Figure 12. The correlation between the two values is -0.09 but it becomes -0.36 if the data from mixtures Cs are not considered. If even the mixture A1 is eliminated the correlation does not improve as it is 0.09. It is clear that the correlation is very poor. This is unfortunate as a good correlation would validate the hypothesis that the concrete mixing truck measurements could be used for estimating the plastic viscosity.



Figure 11: Yield values from concrete mixing truck and rheometer measurements. The circled points are from mixture C, the squared point is the SCC mixture F3, and the point marked with a cross is mixture A1.



Figure 12: Plastic viscosity values from concrete mixing truck and rheometer. The circled points are from mixture C and the squared point is the SCC mixture F3.

4.3.2. Rheological value measurements and mixture composition

Figure 13 and Figure 14 show the values H_t and G_t for the truck (Table 6) and H_R and G_R for the rheometer (Table 7) in a graphical form. It should be noted that some of the data were scaled to allow a better visualization of the trends. The concrete mixing truck data were divided by a factor of 10 and the rheometer data were multiplied by a factor 10. The purpose of the graphic representation is to see if there are trends due to mixture composition changes. Each mixture will be examined separately.

- <u>Mixture A</u>: water was added in increments. Therefore, the yield stress and the viscosity should decrease from mixture A1 to mixture A4. This is what is observed for the rheometer values. For the concrete mixing truck values, the yield stress decreases, but the plastic viscosity increases from A1 to A2 and then decreases for A3 and A4.
- <u>Mixture B</u>: water was added in increments. Therefore, the yield stress and the viscosity should decrease from mixture B1 to mixture B4. The yield stress does decrease for the rheometer and the concrete mixing truck data. The plastic viscosity decreases from B1 to B3 but increases for B4 for the rheometer, while it increases from B1 to B2 and decreases for B3 and B4.
- <u>Mixture C:</u> HRWRA was added in increments but this mixture was found to be segregated due to an error in batching (Figure 6). The addition should decrease the yield stress and depending on the admixture it might decrease or increase or

not affect the plastic viscosity. The yield stress decreased for both the concrete mixing truck and the rheometer but the rheometer showed negative values. The plastic viscosity trend is reversed between the concrete mixing truck and the rheometer: the concrete mixing truck sees an increase from C1 to C2 and it is stable; the rheometer saw a decrease from C1 to C2 to C3.

- <u>Mixture D</u>: D2 was obtained by adding water and D3 and D4 by addition of VMA. Therefore, the yield stress should decrease for D2 and then could be stable for D3 and D4. The plastic viscosity should decrease for D2 and then increase for D3 and D4. The yield stress seems to decrease for D2 and then increase for the rheometer while the concrete mixing truck sees a constant increase. The plastic viscosity is stable for the concrete mixing truck and is decreasing for the rheometer.
- <u>Mixture E</u>: HRWRA was added in increments (repeat of mixture C). The addition should decrease the yield stress and depending on the admixture it might decrease or increase or not affect the plastic viscosity. A decrease of the yield stress was seen both for the concrete mixing truck and for the rheometer. The rheometer saw an increase of the plastic viscosity followed by a decrease while the concrete mixing trucks saw a constant increase.
- <u>Mixture F</u>: addition of VMA and then the mixture became SCC. The yield stress should not change for F2 and the plastic viscosity should increase. For F3, the yield stress should decrease to zero and the plastic viscosity might be high. The yield stress follows the expected trend. The plastic viscosity increases with the concrete mixing truck only for F3 but there are no significant changes for the rheometer data.

Table 8 attempts to summarize the above observations. It is obvious that the yield stress follows the trends expected for five of the six mixes. The only one that that seems a problem is the mixture D where VMA was added. For the plastic viscosity, it seems very hard to predict and the trends are often either contradictory or not correlated between the rheometer and the concrete mixing truck. Also, it seems that in the mixture tested the plastic viscosity does not always follow the expected trends, predicted from the chemical or water addition for either or both the rheometer and the concrete mixing truck. Therefore, it is suggested that further tests concentrate in studying the plastic viscosity by preparing mixtures that differ mainly by their plastic viscosity even if the yield stress is not affected.

Table 8: Summary of trends for rheological parameters and mixture composition. The trends that are as expected for both devices are in bold and the trends that were as expected for either device separately are underlined. Only two mixtures showed both the yield stress and the viscosity as expected and they are highlighted in grey.

Mixture	Rheometer	Concrete mixing truck	Conclusions
А	Yield stress as expected	<u>Yield stress as expected;</u>	Yield stress OK for both
	Viscosity as expected	Viscosity not as expected	Concrete mixing truck
		for all mixes	viscosity mixed results
В	Yield stress as expected	Yield stress as expected	Yield stress OK for both
	Viscosity OK for B2-B3	Viscosity OK for B3-B4	Viscosity not clear
С	Yield stress as expected	Yield stress as expected	Yield stress OK for both
	Viscosity decreases as	Viscosity not as expected	Viscosities reverse!
	expected		Segregation
D	Neither yield stress or	Neither yield stress or	Nothing as expected
	viscosity as expected	viscosity as expected	
Е	Yield stress as expected	Yield stress as expected	Yield stress OK
	Viscosity different than	Viscosity different than	Viscosity reverse!
	concrete mixing truck	rheometer	-
F	Yield stress as expected	Yield stress as expected	Concrete mixing truck:
	Viscosity F2 should be	Viscosity as expected	ОК
	higher than F1		Rheometer: viscosity F2
			strange but yield stress
			OK



Figure 13: Influence of mixture design on rheological parameters; Mixture A, B, C, D. Some values were scaled to allow a better visualization of the data. Note: the t stands is for the concrete mixing truck values and r is for the rheometer values.



Figure 14: Influence of mixture design on rheological parameters: Mixtures E and F. Some values were scaled to allow a better visualization of the data. Note: the t stands is for the concrete mixing truck values and r is for the rheometer values.

5. Discussion and Conclusions

The idea to use a concrete truck as a rheometer is not an easy idea to implement. The series of tests presented in this paper are inconclusive because not even the rheometer was able to detect changes in the concrete that were expected. In Table 8 only two tests, one for the rheometer and one for the concrete truck, lead to comments such as "Yield stress as expected" and "Plastic viscosity as expected". The mixtures as selected and as prepared lead that even the rheometer was not producing trends "as expected" in most cases. This was surprising as the devices has been routinely used to detect trends and correlates well with other rheometers [2, 3].

The possible reasons for these poor performances, even by the rheometer, are probably related to the methodology of testing:

- Concrete was not sampled correctly from the truck. Usually a good concrete sample is taken from the middle of the truck discharge. Here samples were taken from the beginning, to preserve most of the load for future testing;
- The concrete was not sufficiently mixed in the truck after the addition of chemical admixtures; therefore the admixture was not evenly distributed in the concrete.
- The rheometer measurements were done with decreasing speed as it is traditionally done, while the truck measurements were done with increasing speed. This might explain the difference in trends observed with the rheometer and the truck (see Table 7)
- To shorten the truck measurement time, fewer measurement points were taken with the truck than with the rheometer. Possibly too few points were taken to ensure a correct calculation of the plastic viscosity.

In light of these findings, this technique is not yet to be discarded, but instead more careful testing should be made. Two main suggestions for future testing could be:

- A new batch should be prepared for each concrete composition and the sample for the rheometer should be taken in the middle of the discharge.
- Use decreasing speed with the truck instead of increasing and more points should be measured per test.

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