

Measuring the rheological transition by the Rheocable sounding method

Report of the tests carried out in the laboratories of Flanders Hydraulics Research

The tests took place in the Sludge Test Tank (STT) of Flanders Hydraulic Research (FHR) on Thursday the 10th of June 2010 from about 1000h a.m. to 1600h p.m.

Attending for THV Nautic were Dr. ir. P. Brabers and ir. M. Druyts .

Attending for FHR was MSc. St. Claeys.

1. Situation in the Sludge Test Tank (SST).

For a description of the sludge test tank, reference is being made to the documentation of the Flanders Hydraulic Research laboratory.

The situation in the tank at time of tests was described by FHR as follows :

- Top water level 0
- Top fluid mud - 45 cm
- Top consolidated mud - 85 cm
- Bottom level tank -194 cm

Furthermore, following data regarding density and viscosity in the tank were made available by FHR: see Appendix 1/1 and 1/2.

For the specification of the measurement procedures and – instruments, reference is being made to the information by FHR: for rheology see Appendix 1/3, for density see Appendix 1/4.

Comment

The data of Appendix 1/1 and 1/2 are graphically represented in the figures of Appendix 1/5 (maximum shear stress) and 1/6 (density).

The shear stress shows a transition between the level of -85 cm and -97.5 cm. If we introduce these same levels in the graph 1/6, it can be observed that this rheological transition level corresponds also to a density transition level.

In realistic field conditions, this density transition level usually cannot be observed because the density probes can only penetrate superficially in the consolidated mud.

Appendix 1/7 shows the correlation between the rheological parameter and the density at the same depth in the tank. It clearly shows that fluid mud and consolidated mud indeed are marked by a very different relationship between density and rheological characteristics.

2. Rheocable tests: descriptions.

2.1 The Rheocable test version.

Due to the limited dimensions in the test tank, compared with in situ conditions, it was not possible to use the standard Rheocable array one of the more important reasons being the very limited depth in the test tank (approximately 80 cm).

Therefore, during the tests, an adapted (improvised) version of the Rheocable was used, the main difference being the absence of components for resistivity measurements. The photo shows the 'test' version of the Rheocable: a weight of about 5 kg, with attached to it the CDT for pressure measurement.

It was the intention to isolate the CDT from the environment and put it in contact with the water column, by small tubes (ventilation tubes), above the fluid mud in order to measure directly the correct water pressure, not interfered by the density of the fluid mud.

This array was disturbed during the tests: this item will be discussed later at the occasion of the comments on each individual test. The photo shows the test Rheocable without the ventilation tubes.



The next photo shows the real Rheocable array, with elements for the resistivity measurement, with ventilation tubes and with a rubber hose protecting the pressure sensor and lead weights of 20 kg.



The next photo shows the recording equipment on top of the test tank.



2.2 The test.

Next photo shows a general view of the top of the test tank, still covered. About half a meter under the cover, when removed, is the free surface of the tank extending over a length of about 8 meters.



A gangway, crossing the tank, is visible in the background. This gangway is movable by hand and was used to tow the test Rheocable over the length of the tank at different velocities.

The average speed of the test run was measured by means of a stopwatch.

During the test runs, the measured depth of the test Rheocable is recorded: the recording frequency is 40 kHz.

Remark.

Before the test runs with the Rheocable were carried out, tests with the Accelerometer probe were performed. It can therefore not be excluded that during each of the test runs, the Rheocable would hit some irregularities in the interface between fluid mud and consolidating mud, left there by the Accelerometer probe tests.

3. Test results.

3.1 Test run 1.

The average velocity of the Rheocable is **0.48 m/s**.

The result is shown in Appendix 3.1a.

The starting position of the Rheocable is about 30 cm lower than the interface fluid mud – consolidating mud: it has penetrated under its own weight in the consolidating mud.

In the acceleration phase, the Rheocable fluctuates and evolves towards a fixed position related to the interface. This position is maintained in the constant velocity phase.

Appendix 3.1b shows the histogram of the recorded differences between Rheocable and interface in the constant velocity phase. The distribution has a normal character, with modus at -8 cm.

3.2 Test run 2.

The average velocity of the Rheocable is 0.47 m/s.

The result is shown in Appendix 3.2.

This test run has failed, the cause being a malfunction of the ventilation tubes isolating the CDT: the top end of the tubes appeared above the water surface during the test run.

Two runs – the numbers 2 and 3 - were needed to detect the exact nature of the failure: these test runs are considered invalid and are not reported.

3.3 Test run 3'.

The average velocity of the Rheocable is 0.47 m/s.

The result is shown in Appendix 3.3'a.

The acceleration phase is different: the Rheocable starts from a position in the transition area and needs to descend for contact with the consolidating mud.

Also in this situation, the Rheocable evolves towards a fixed position in the constant velocity phase.

Appendix 3.3'b shows the histogram of the recorded differences between Rheocable and interface in the constant velocity phase. The distribution has a normal character, with modus at -4 cm.

3.4 Test run 4.

The average velocity of the Rheocable is 0.90 m/s.

The result is shown in Appendix 3.4a.

The evolution of the Rheocable with respect to the position of the interface is not clear or stable in this test run, which was executed with a velocity almost 3 times higher than the former test run.

This observation is confirmed by the histogram of the deviations: see Appendix 3.4b. The histogram shows two different modi: one at about -17 cm and the other one at -8.5 cm.

At the end of this tow it was observed that the ventilation tubes had become detached from the isolating cell of the CDT, due to the high(er) tow velocity. Consequently, the CDT pressure had become subjected directly to the in situ pressure, including the density of the fluid mud.

It was decided to continue the test runs without CDT isolation from the fluid mud phase. The pressure measured in the following test runs, has been corrected accordingly.

The result of this test run is not taken into consideration for evaluation purposes.

3.5 Test run 5.

The average velocity of the Rheocable is 0.62 m/s.

The result is shown in Appendix 3.5a.

The start position of the Rheocable is about 30 cm lower than the interface fluid mud – consolidating mud: it has penetrated under its own weight in the consolidating mud.

In the acceleration phase, the Rheocable fluctuates and evolves towards a fixed position related to the interface. This position is maintained in the constant velocity phase.

Appendix 3.5b shows the histogram of the recorded differences between Rheocable and interface in the constant velocity phase. The distribution has a normal character, with modus at -5 cm.

3.6 Test run 6.

The average velocity of the Rheocable is 0.71 m/s.

The result is shown in Appendix 3.6a.

The starting position of the Rheocable is about 30 cm lower than the interface fluid mud – consolidating mud: it has penetrated under its own weight in the consolidating mud.

In the acceleration phase, the Rheocable fluctuates and evolves towards a fixed position related to the interface. This position is maintained in the constant velocity phase.

Appendix 3.6b shows the histogram of the recorded differences between Rheocable and interface in the constant velocity phase. The distribution has a normal character, with modus at -5 cm.

3.7 Test run 7.

The average velocity of the Rheocable is 0.85 m/s.

The result is shown in Appendix 3.7a.

The velocity is high: acceleration and deceleration phases take significantly more time when compared with the foregoing test runs. Consequently, due to the limited length of the sludge test tank, the phase of constant velocity is limited.

In this phase of constant velocity, the position of the Rheocable is stable again with respect to the interface, but in this case with a position 5 cm above the interface in the transition zone: the cable is floating. See also Appendix 3.7b.

Comment.

In this test run 7, the tow velocity has exceeded the velocity window where the Rheocable is in contact with the consolidating mud. (resistivity measurement would have indicated this step very clearly)

In this floating condition, the depth position of the Rheocable depends directly on the tow velocity and on the viscous drag, and on these two parameters alone. Comparing this position at the same tow velocity, but in the absence of a fluid mud layer, enables the calculation/measurement of the difference in viscous drag.

This difference in viscous drag is related to the viscous properties of the fluid mud, therefore with the efficiency of the ship's propellers and thus with the ship's manoeuvrability: reference is being made to the similar case of a dredge pump. Very different mixture velocities apply when dredging/pumping fluid mud or consolidating mud.

Independent from any possible scientific considerations regarding the rheological characteristics of the Nautical Depth, the Rheocable has definitively the potential to measure its exact level.

3.8 Test run 8.

The average velocity of the Rheocable is 0.33 m/s.

The result is shown in Appendix 3.8a.

The starting position of the Rheocable is about 25 cm lower than the interface fluid mud – consolidating mud: it has penetrated under its own weight in the consolidating mud.

In the acceleration phase, the Rheocable fluctuates and evolves towards a fixed position related to the interface. This position is maintained in the constant velocity phase.

Appendix 3.8b shows the histogram of the recorded differences between Rheocable and interface in the constant velocity phase. The distribution has a normal character, with modus at -5 cm.

3.9 Test run 9.

The average velocity of the Rheocable is 1.04 m/s.

The result is shown in Appendix 3.9a.

The velocity is high: the Rheocable floats. Due to the extended accelerating and decelerating phases, it was apparently not possible to reach a period of constant velocity, however small.

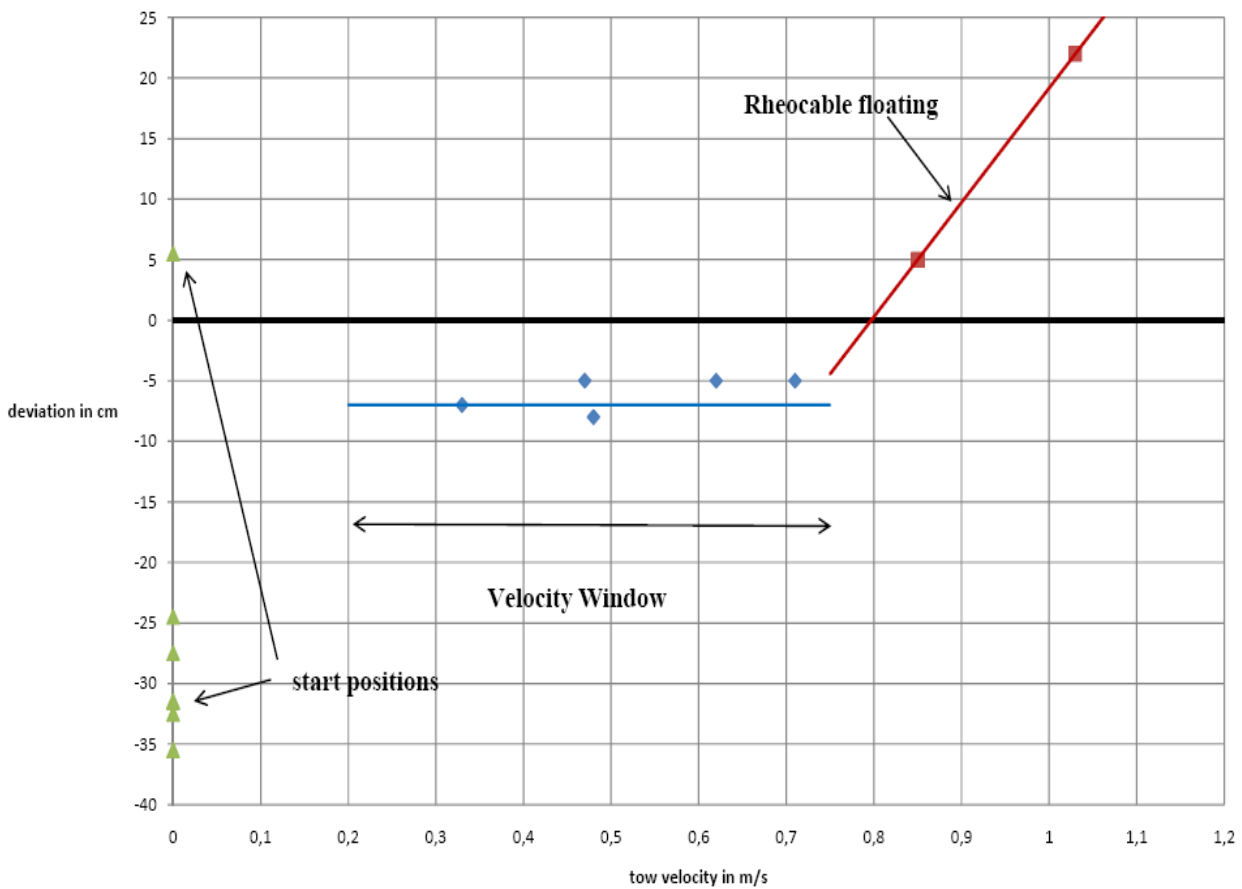
This test run 9 illustrates again the existence of a velocity window.

4. Discussion of the results.

The test results are summarized in the following table:

Test run nr.	Tow velocity m/s	Rheocable position to interface cm
1	0.48	-8
3'	0.47	-5
5	0.62	-5
6	0.71	-5
7	0.85	+5
8	0.33	-7
9	1.03	+22

The results are visualized in the following graph:



The tests confirm the existence of a velocity window, such that towing velocities in the window generate the same depth position of the Rheocable with regard to the interface between fluid mud and consolidating mud.

At the lower end of the window velocity, all test runs minus test run 3' show that the Rheocable penetrates in the consolidating mud at zero tow velocity and that already at a minimal towing velocity, the Rheocable moves up to its fixed interface position.

Once completed the acceleration phase, the position of the Rheocable remains fixed – give and take some 2 or 3 cm (!) – fully independent of the varying tow velocity up to a velocity of about 0.75 m/s.

At higher velocity, the Rheocable starts to float as experienced in test runs 7 and 9.

Conclusion.

The existence of a low velocity window where the Rheocable invariably takes the position at the interface between fluid mud and consolidating mud has been demonstrated.

This demonstration proves not only the validity of the measuring principle, but also that the Rheocable is fully capable of implementing these measuring principles.

Done at Bruges, the 9th of December 2010,

ir. Marcus Druyts

Dr. ir. Peteralv Brabers

Additional comments.

1. About the test tank situation.

Some comments deny that the situation in the test tank is representative, because of the procedures applied to create the situation. It supposedly doesn't take into account the existence of a second rheological transition in the fluid mud. Consequently, according to these comments, the test results in the sludge test tank would not be applicable in realistic field conditions and would leave a broad spectrum of situations untested.

Following observations can be made:

- In our experience, areas where maintenance dredging activities are carried out with some frequency, do show familiar conditions as in the STT, i.e. most importantly a small transition area between fluid mud and consolidating mud.
- With exception for relatively rare geological situations involving a state of disequilibrium caused by rapid geological subsidence, the presence of significantly thick fluid mud layers is always caused by dredging activities; if not a state of equilibrium would have been installed. In this state of equilibrium, for all practical purposes, no fluid mud layer would show up.
- In our experience, doing Rheocable surveys, no indications were observed up to now of such thing as a second rheological transition in the fluid mud: see also following additional comment.

2. About the Rheocable in floating condition.

Test run 7 shows the Rheocable floating in the transition area. In this situation, the position of the Rheocable can be compared with the floating position at the same velocity in water.

The behaviour of a floating Rheocable is well and accurately known: calibrated mathematical models for the position of the floating cable are available.

Differences in the vertical position of the Rheocable are related to differences in gravity and drag forces on the Rheocable and the latter differences are related to the viscous properties of the fluid mud at the depth measured.

The Rheocable in floating conditions would therefore have the capability to detect a second rheological transition in case there is one.

Viscosity data

shearstress (Pa)	Depth below sludge -5 cm	-5	1,688	2,264	2,917	4,396	6,552	5,893	5,98	6,275	6,723	7,403	8,508	13,62	29,25	74,67
shearstress (Pa)	Depth below sludge -7,5 cm	-7,5	3,841	4,946	6,366	9,603	10,21	9,925	10,19	10,6	11,2	12,07	13,49	17,84	39,71	88,02
shearstress (Pa)	Depth below sludge -10 cm	-10	5,229	6,626	8,569	11,19	11,02	11,24	11,69	12,19	12,88	13,88	15,37	19,38	42,46	90,67
shearstress (Pa)	Depth below sludge -12,5 cm	-12,5	5,649	7,175	9,188	12,61	13,12	13,19	13,62	14,14	14,83	15,88	17,52	21,48	44,26	93,98
shearstress (Pa)	Depth below sludge -15 cm	-15	5,281	7,691	10,26	13,77	13,84	14,05	14,62	15,2	15,95	17,1	18,9	22,89	46,41	96,71
shearstress (Pa)	Depth below sludge -17,5 cm	-17,5	7,886	9,227	12	14,71	14,46	14,69	15,28	15,85	16,63	17,81	19,63	23,51	47,53	98,64
shearstress (Pa)	Depth below sludge -20 cm	-20	12,84	12,74	12,98	14,02	14,67	15,22	15,8	16,37	17,15	18,37	20,26	24,35	46,01	100
shearstress (Pa)	Depth below sludge -22,5 cm	-22,5	11,47	13,56	16,43	22,02	27,62	26,83	26,99	27,42	28,18	29,47	31,66	35,71	54,51	122,8
shearstress (Pa)	Depth below sludge -25 cm	-25	14,71	18,39	23,09	28,04	27,51	27,43	27,91	28,39	29,23	30,65	33,09	37,12	55,26	122
shearstress (Pa)	Depth below sludge -27,5 cm	-27,5	17,55	20,43	25,58	30,96	30,75	30,54	31,02	31,54	32,45	33,93	36,43	40,83	58,2	128,6
shearstress (Pa)	Depth below sludge -30 cm	-30	17,5	18,94	23,13	27,58	27,68	28,08	29,04	29,89	31,04	32,7	35,35	39,54	55,03	126,8
shearstress (Pa)	Depth below sludge -32,5 cm	-32,5	21,66	23,32	30,02	32,28	32,46	32,42	32,94	33,41	34,33	35,87	38,64	43,24	60,61	133,6
shearstress (Pa)	Depth below sludge -35 cm	-35	18,24	21,88	26,27	32,96	34,41	33,87	34,33	34,91	35,93	37,61	40,41	45,09	61,78	141,1
shearstress (Pa)	Depth below sludge -37,5 cm	-37,5	13,61	17,08	20,33	29,21	38,6	37,11	37,22	37,86	38,89	40,63	43,58	48,57	65,28	144,8
shearstress (Pa)	Depth below sludge -40 cm	-40	17,94	21,84	26,76	33,62	35,77	35,93	36,98	37,96	39,36	41,38	44,53	49,77	66,56	157,3
shearstress (Pa)	Depth below sludge -42,5 cm	-42,5	47,93	67,7	72,78	82,45	104,7	135,7	128,4	107,6	107,8	113,9	122,9	137,4	170	258,7
shearstress (Pa)	Depth below sludge -45 cm	-45	60,42	76,02	88,46	108,2	134,8	169,2	181,6	180,6	192,3	207,4	215,2	229,2	252,9	333
shearstress (Pa)	Depth below sludge -47,5 cm	-47,5	235,8	306,3	310,6	323,1	361,1	400	394,2	388,5	403,2	419,8	437	459	489,7	570,6
shearstress (Pa)	Depth below sludge -50 cm	-50	239,3	368,5	403,2	459,6	496,9	516,8	516,2	523,8	528,7	536,2	552,1	569,6	600,3	670,4
shearstress (Pa)	Depth below sludge -52,5 cm	-52,5	491,9	619,1	602,9	604,2	627,7	640,8	648,9	652,7	654,2	661	674,3	693,8	726,8	791,7
shearstress (Pa)	Depth below sludge -55 cm	-55	494,8	613,9	603	609,7	623	625,7	616,8	609,9	606,6	612,7	625,3	644	678,1	738,7
shearstress (Pa)	Depth below sludge -57,5 cm	-57,5	496,5	665,2	646,4	626,4	628,2	625,4	607,2	592,2	588,6	593	607,2	630,5	669	752,3
shearstress (Pa)	Depth below sludge -60 cm	-60	616	700	671	646	648	646	635	619	604,4	604,8	615,2	639	667	728
shearstress (Pa)	Depth below sludge -65 cm	-65	672	741	715	682	676	675	661	642	619	609,8	615	627	661	721
shearstress (Pa)	Depth below sludge -70 cm	-70	628	667	591	545	581	570	555	528	513	512	519	533	565	657
shearstress (Pa)	Depth below sludge -75 cm	-75	709	786	711	669	706	721	721	709	691	686	693	712	745	820
shearstress (Pa)	Depth below sludge -80 cm	-80	759	851	777	712	736	737	719	702	678	676	682	692	719	789
shearstress (Pa)	Depth below sludge -85 cm	-85	782	835	721	645	689	708	710	688	677	675	677	694	719	771
shearstress (Pa)	Depth below sludge -90 cm	-90	880	1.004	935	863	879	871	827	811	795	779	782	798	832	854
shearstress (Pa)	Depth below sludge -95 cm	-95	827	948	871	809	826	845	812	798	784	792	807	809	832	858
shearstress (Pa)	Depth below sludge -100 cm	-100	945	1.091	1.101	1.034	1.022	981	934	915	902	896	897	902	924	959
shearstress (Pa)	Depth below sludge -105 cm	-105	1.177	1.217	1.096	1.018	988	1.020	995	958	945	936	941	957	994	1.045
shearstress (Pa)	Depth below sludge -110 cm	-110	1.221	1.322	1.274	1.199	1.217	1.225	1.212	1.182	1.144	1.125	1.115	1.123	1.141	1.208
shearstress (Pa)	Depth below sludge -115 cm	-115	1.343	1.396	1.289	1.211	1.297	1.359	1.349	1.317	1.282	1.249	1.245	1.240	1.260	1.321
shearstress (Pa)	Depth below sludge -120 cm	-120	1.551	1.621	1.503	1.392	1.467	1.490	1.464	1.413	1.373	1.360	1.326	1.315	1.332	1.360
shearstress (Pa)	Depth below sludge -125 cm	-125	1.591	1.613	1.476	1.356	1.431	1.432	1.404	1.378	1.363	1.359	1.360	1.342	1.370	1.403
shearstress (Pa)	Depth below sludge -130 cm	-130	1.500	1.698	1.696	1.609	1.617	1.642	1.638	1.611	1.596	1.595	1.584	1.584	1.594	1.659
shearstress (Pa)	Depth below sludge -135 cm	-135	1.736	1.739	1.600	1.479	1.433	1.433	1.344	1.285	1.253	1.223	1.222	1.220	1.234	1.283
shearstress (Pa)	Depth below sludge -140 cm	-140	1.955	2.051	1.878	1.771	1.843	1.885	1.839	1.762	1.701	1.679	1.658	1.654	1.642	1.709

Density data

staalnr.	Potnr	Hoogte	Densiteit ongeroerd	Densiteit na roeren
SC2010008632	1,1	-5	1,1246	1,1198
SC2010008633	1,2	-7,5	1,1294	1,1287
SC2010008634	1,3	-10	1,1280	1,1353
SC2010008635	2,1	-12,5	1,1388	1,1366
SC2010008636	2,2	-15	1,1367	1,1394
SC2010008637	2,3	-17,5	1,1402	1,1427
SC2010008638	2,4	-20	1,1476	1,1391
SC2010008639	3,1	-22,5	1,1432	1,1301
SC2010008640	3,2	-25	1,1558	1,1418
SC2010008641	3,3	-27,5	1,1446	1,1527
SC2010008642	3,4	-30	1,1332	1,1454
SC2010008643	4,1	-32,5	1,1377	1,1505
SC2010008644	4,2	-35	1,1339	1,1339
SC2010008645	4,3	-37,5	1,1594	1,1598
SC2010008646	4,4	-40	1,1521	1,1592
SC2010008647	5,1	-42,5	1,1926	1,2051
SC2010008648	5,2	-45	1,2286	1,2311
SC2010008649	5,3	-47,5	1,2368	1,2245
SC2010008650	5,4	-50	1,2390	1,2436
SC2010008651	6,1	-52,5	1,2540	1,2367
SC2010008652	6,2	-55	1,2421	1,2569
SC2010008653	6,3	-57,5	1,2411	1,2480
SC2010008654	6,4	-60	1,2552	1,2517
SC2010008655	7,1	-65	1,2458	1,2578
SC2010008656	7,2	-70	1,2550	1,2542
SC2010008657	8,1	-75	1,2448	1,2484
SC2010008658	8,2	-80	1,2626	1,2643
SC2010008659	9,1	-85	1,2644	1,2534
SC2010008660	9,2	-90	1,2632	1,2554
SC2010008661	10,1	-95	1,2725	1,2598
SC2010008662	10,2	-100	1,2720	1,2692
SC2010008663	11,1	-105	1,2741	1,2738
SC2010008664	11,2	-110	1,2832	1,2803
SC2010008665	12,1	-115	1,2801	1,2820
SC2010008666	12,2	-120	1,2845	1,2922
SC2010008667	13,1	-125	1,2920	1,2938
SC2010008668	13,2	-130	1,3056	1,2941
SC2010008669	14,1	-135	1,3248	1,3111
SC2010008670	14,2	-140	1,2961	1,2873
SC2010008671	15	-145	1,2567	1,2468

1.1 Rheology

1.1.1 Rheology equipment and analyses

The rheometer Anton Paar Physica MCR 301 has been used to determine the rheological parameters from the sludge. The MCR 301 is a shear stress and shear rate controlled device (see technical sheet in **Fout! Verwijzingsbron niet gevonden.**).



In order to avoid slip of the bob in the sludge sample, no cylinder but vane is used. Particulate matter with large grain-sizes also gives bad readings

when used with a cylinder-bob and cup. The narrow gap between the two parts results in wrong results (Toorman, E.A. (1994)).

To visualize the some of the rheology parameters a protocol was needed to be set. To compare this study with other research, we have chosen for a shear-rate controlled test. The amount of data-point and shear rate range was determined taking the following into consideration:

- Because of scheduling the rheological analyses in the highly occupied laboratory, a good relation was found between the execution of the analyses (time), amount of data points (resolution) and range.
- A maximum of 3 vertical profiles of a length of +/- 2 m, with a sub sampling of every 10 cm result in analysing 60 samples (3 profiles x 2 m x 10 samples/m). In a 8 hour working day, this results in 8 minutes/sample + manipulation and temperature stabilisation time. To visualise the yield-stress part of a rheogram, a focus on the lower shear-rate part was needed. To find the equilibrium stage of the rheogram, enough high shear-rate points were also needed.
- The following set-up was chosen:
 - o 14 measurement points with an interval duration of 219,4 sec (4 minutes) + manipulation and temperature stabilisation time
 - o The applied shear rate measurement-point starts from 0,1 1/s and increases logarithmical to a shear rate of 1000 1/s (see Figure 2).
 - o The exposure time start at 60 seconds and decreases logarithmical to 1 second for the last shear rate (Figure 1).

=> This result in the following points 0,09999; 0,2031; 0,4124; 0,8376; 1,701; 3,455; 7,017; 14,25; 28,94; 58,78; 119,4; 242,5; 492,4; 1.000 1/s

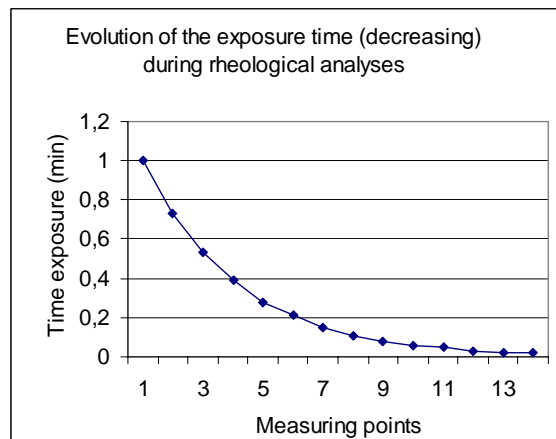


Figure 1 – Evolution of the exposure time during rheological analyses

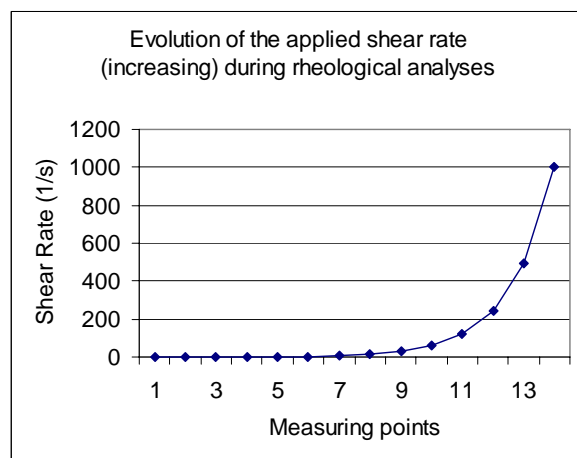


Figure 2 – Evolution of the applied shear rate during rheological analyses

The 'shear-rate applied versus shear stress' flow-charts are created at a temperature of 16 ° C. This temperature was reached and maintained using a Peltier element. The samples are very carefully manipulated not to disturb them (even keeping the 'natural' produced gasses into the sludge). Attention was paid to prevent inclosing air bubbles.

1.1 Density

1.1.1 Density equipment

The DMA 38 from Anton Paar has been used for density measurement.

- Density range 0 tot 3 g/cm³ ± 0,001 g/cm³
- Temperature range 15°C tot 40°C ± 0,2°C

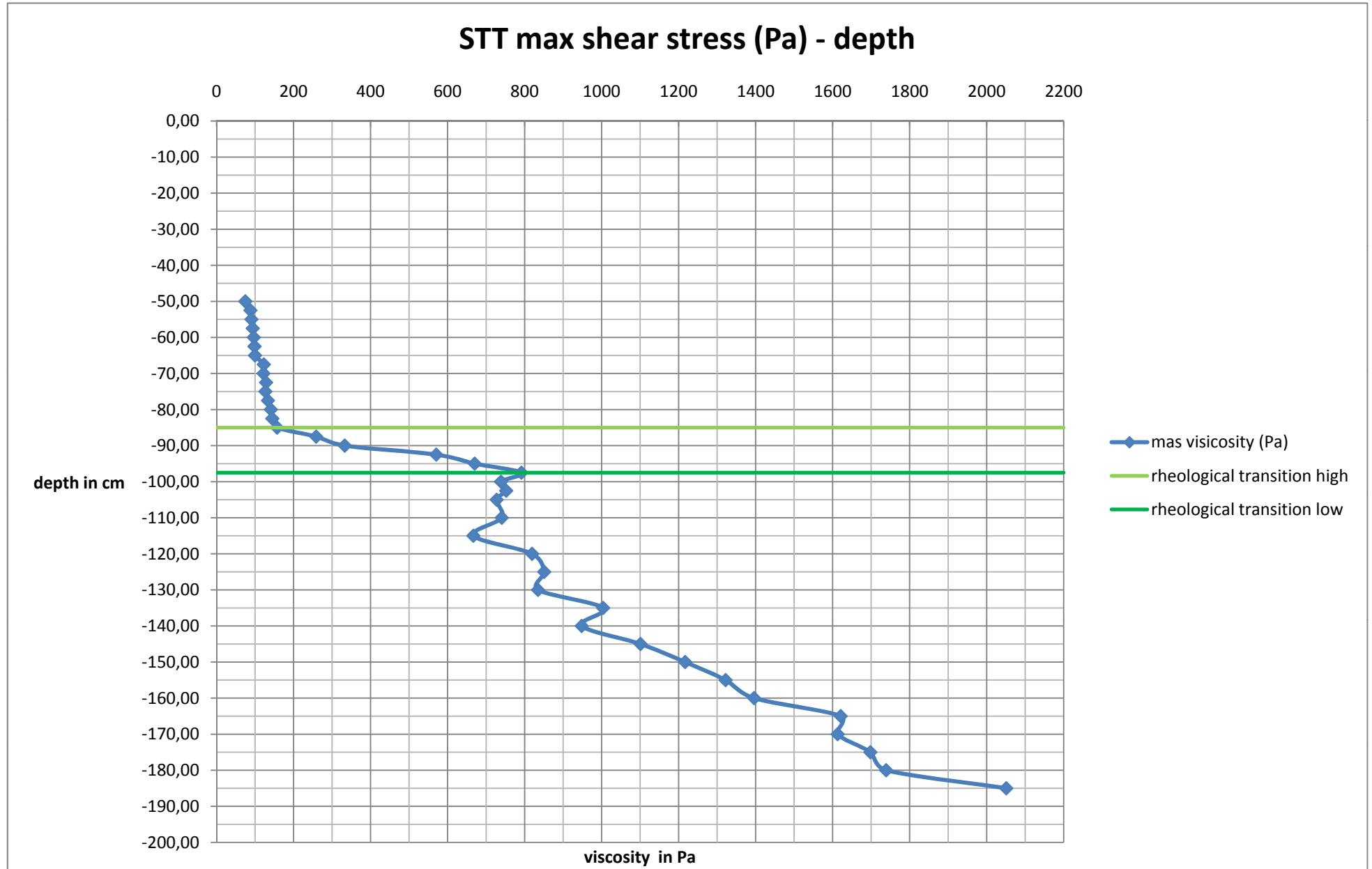
Setup and errors:

- All analyses have been executed at 16° C
- Gas bubbles in the samples gives wrong readings and an error display: "please fill".
- High density sludge is very difficult to pump into the small tuning tube, and obstruction can occur due to too large debris.
- When sampling the whole sludge column into two vertical Beekersampler profiles (no tube available to sample whole column at ones), errors at the overlapping height occurs.

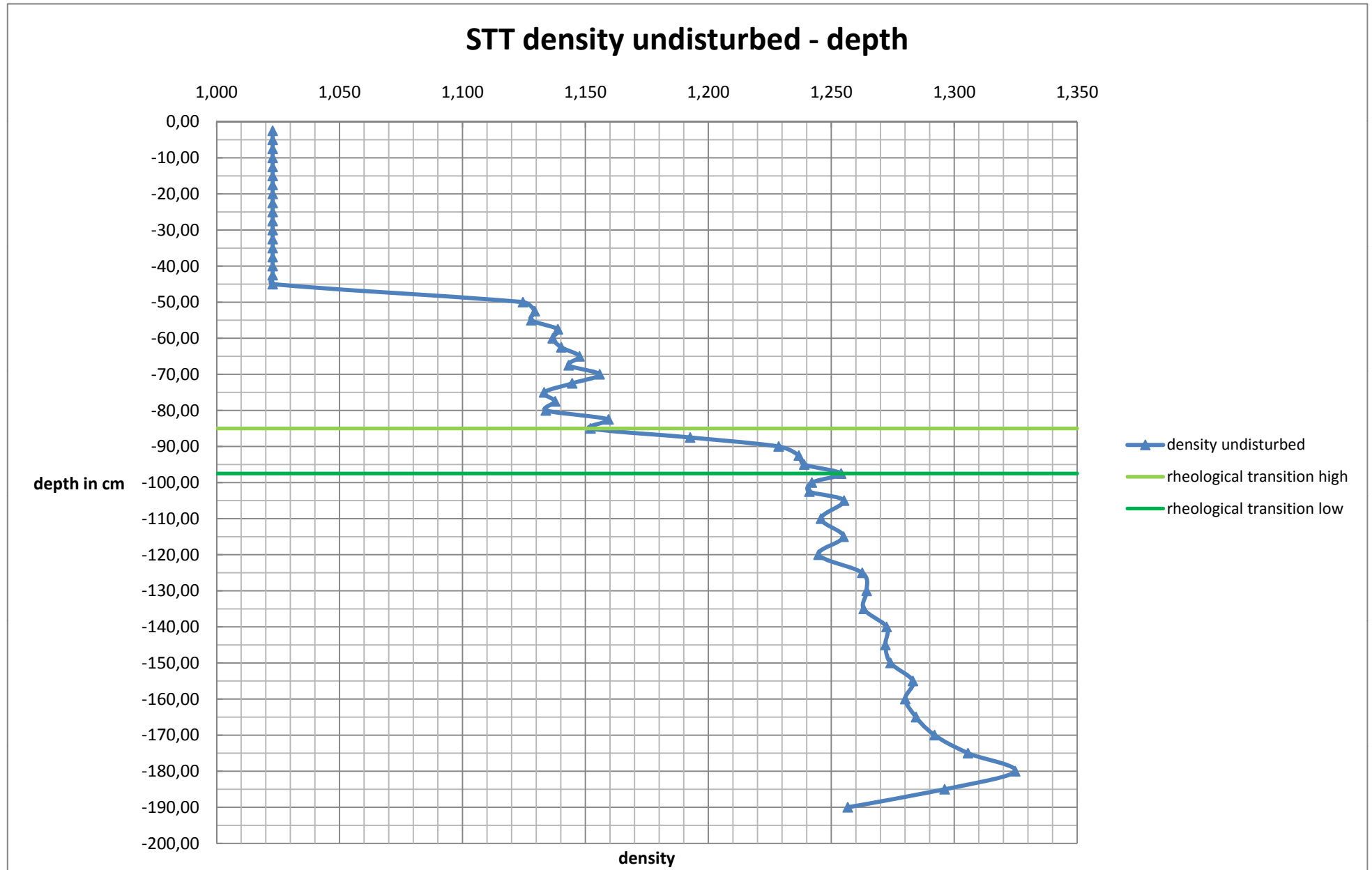


Figure 1 – DMA 38 from Anton Paar

Max. shear stress - depth



Graph density - depth



Correlation density - shear stress

