Why do settling and yield stress of mud differ in european ports?

Kirichek, Alex ; Shakeel, A.; Chassagne, C.; Gebert, J.

Publication date
2022

Document Version
Final published version

Published in
Proceedings to WODCON XXIII

Citation (APA)
Kirichek, A., Shakeel, A., Chassagne, C., & Gebert, J. (2022). Why do settling and yield stress of mud differ in european ports? In *Proceedings to WODCON XXIII* https://www.dredging.org/resources/ceda-publications-online/conference-proceedings/abstract/1115

WHY DO SETTLING AND YIELD STRESS OF MUD DIFFER IN EUROPEAN PORTS?

Kirichek[1], A. Shakeel[2], C. Chassagne[3] and J. Gebert[4]

Abstract: In some ports and waterways, hindered (delayed) settling of mud suspended in the water phase can be detected. Hindered settling phenomena are typically linked to a combination of sediment properties, suspended sediment concentration or density, hydrodynamic conditions, presence or absence of organic bridging between mud particles and the properties of the water phase such as salinity. Hindered settling may be desired or undesired for maintenance of the nautical depth - it might be beneficial if the properties meet the nautical bottom criteria for safe navigation and maneuvering; however, in case fast settlement and consolidation is necessary for efficient dredging, hindered settling is disadvantageous.

Yield stress of mud has been extensively studied for the nautical bottom and port maintenance purposes over the last years. New rheological protocols have been developed for measuring rheological characteristics of mud deposits and analysing the structural recovery of mud. Additional knowledge has been gained from studying the role of density and organic matter and further comparison to the yield stresses measured in the laboratory and in the field.

This work connects the knowledge of settling phenomena and rheology. Settling and rheological behaviour of mud from different European ports has been extensively studied. Variation of yield stress values in different ports has been studies by correlating rheological properties and settling of mud to other key sediment properties like density, mud composition, clay content and clay type, total organic carbon (TOC) and organic matter degradation.

Key words: Nautical bottom, Rheology, Organic matter, Density, Maintenance Dredging

[1] Delft University of Technology, the Netherlands, o.kirichek@tudelft.nl
[2] Delft University of Technology, the Netherlands, a.shakeel@tudelft.nl
[3] Delft University of Technology, the Netherlands, c.chassagne@tudelft.nl
[4] Delft University of Technology, the Netherlands, j.gebert@tudelft.nl

1 INTRODUCTION

Mud is a cohesive, water-saturated material consisting of different clay minerals, sand, silt and organic matter, which is mainly produced by living microorganisms. Typically, mud deposits are exposed to hydrodynamic forces, which are either triggered by natural conditions (tides, currents, bioturbation) or by human-caused activities (ship navigation and dredging) resulting in formation of soft fluid mud layers that can be potentially navigable (Kirichek et al., 2018). With time, theses fluid mud layers settle and build up strength due to settling and consolidation processes.

From the rheological point of view, the strength of soft mud deposits is related to the yield stress that is measured. There are numerous rheological protocols to measure the yield stress of natural mud in the laboratory. Furthermore, there are different definitions of the yield stress can be found in the literature. In this work, we focus on the yield stresses that correspond to the strength of mud and rheological protocols that have been optimized for measuring the yield stresses of soft natural mud deposits.

The yield stress of soft mud can be estimated by conducting rheological characterization tests on mud samples in laboratory or by conducting field surveys and employing in-situ profilers (e.g. Rheotune, Graviprobe). The knowledge on hindered settling of mud can also be obtained in laboratory by means of settling tests and in-situ by analysing time series of acoustic and seismic survey data. The water-mud interface (lutocline) in ports and waterways can be monitored either by conventional in-situ acoustic methods such as high-frequency multi-beam echo-sounding (Kirichek and Rutgers, 2022) or by more novel techniques such as Distributed Acoustic Sensing and fibre optics that are currently tested (Buisman et al., 2022).

The knowledge of settling and strength of mud deposits can be very useful for defining optimal maintenance dredging strategies in ports and waterways. For instance, soft mud deposits with weak shear strength (fluid mud) are suitable for navigation by means of adapting the PIANC's nautical bottom approach (PIANC, 2014). However, in case fast settling and consolidation is necessary for efficient dredging, hindered settling is disadvantageous.

Settling and strength of mud typically differ from one port to another. Reviewing existing data, the goal of this study is to investigate the influence of several key sediment parameters including density, settling, clay content and clay type, TOC and organic matter degradation on the rheological properties and hindered settling of mud. We show that the rheological properties and settling of mud from Port of Hamburg, Port of Emden, Port of Rotterdam and Port of Antwerp are significantly different due to variation in sediment properties.

2 RHEOLOGY AND SETTLING BEHAVIOUR

2.1 Rheological protocol

Several rheological protocols have been reported in literature to determine the yield stress of mud. These protocols include shear rate ramp-up (Xu and Huhe, 2016; Yang et al., 2014), shear stress ramp-up (Shakeel et al. 2020a; Wurpts and Torn, 2005), and Claeys et al. protocol (Claeys et al., 2015). Shear rate/shear stress ramp-up methods are fast and easy to perform. On the other hand, Claeys et al. protocol is based on several cycles of selected shear rates along with high shear rate steps in-between the cycles, with a total experimental time of about 15 – 20 min. The outcome of the different protocols in terms of shear stress as a function of shear rate or apparent viscosity as a function of shear stress for Port of Hamburg mud is shown in Figure 1. The values of static and fluidic yield stresses obtained from the two viscosity declines of these curves (Figure 1b) are presented in Table 1. Static yield stress is related to a structural re-arrangement of flocs in mud at low shear rates and fluidic yield stress corresponds to the (shear) strength of mud when the floc structure is broken (Shakeel et al., 2020c). It can be seen from Table 1 that higher yield stress values are obtained from stress ramp-up test, ramp-up step of shear rate ramp up and ramp down (CSRT) test and increasing equilibrium flow curve (EFC) test. This is linked to the fact that these methods deform mud samples from an almost undisturbed state to an almost fully disturbed state. These methods are, therefore, suitable to measure the yield stresses of mud close to in-situ conditions. However, the determination of a static yield point is difficult in case of ramp-up step of the CSRT test (due to the scattering of the initial apparent viscosity as function of stress points) and the increasing EFC test is time-consuming (~ 20 min). Therefore, it is recommended to use stress ramp-up test for analysing the in-situ yield stresses of mud for ports and waterways applications. The yield stress values obtained from the rest of the methods (i.e., Claeys et al., decreasing EFC, pre-shear and ramp-down step of CSRT) are lower, which indicates the extensive structural breakdown of the samples during analysis.

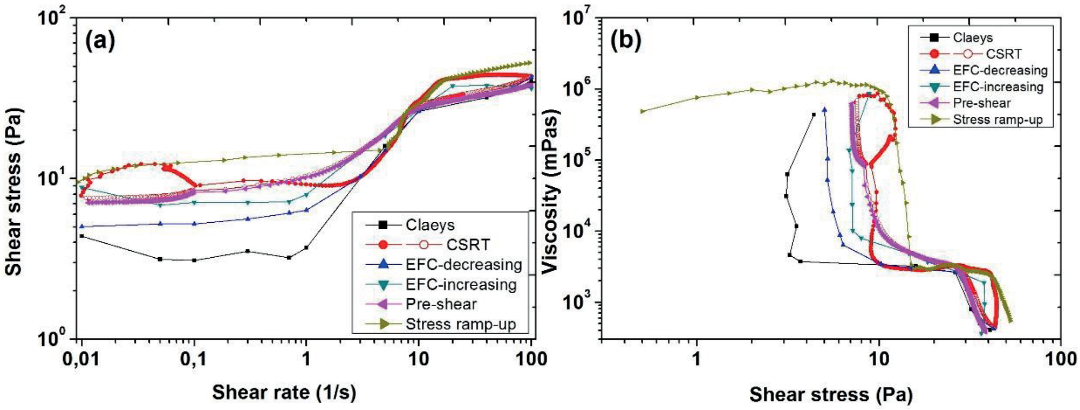

Figure 1. (a) Shear stress as a function of shear rate and (b) apparent viscosity as a function of shear stress for mud sample collected from port of Hamburg using Couette geometry; solid symbols in CSRT protocol represent the ramp-up and the empty symbols represent the ramp-down (Shakeel et al., 2021b)

Table 1. Static and fluidic yield stress values of mud sample from port of Hamburg obtained from viscosity declines with Couette geometry for different protocols (Shakeel et al., 2021b)

Method	**Static Yield Stress (Pa)**	**Fluidic Yield Stress (Pa)**
Claeys et al. protocol	3.1-4.4	26
CSRT-ramp up	9.0-12.3	40
CSRT-ramp down	7.6	29
EFC-decreasing	5.2	26
EFC-increasing	7.1	38
Pre-shear	7.1	27
Stress ramp-up	11	40

2.2 Variation of yield stress values in ports

The dependence of yield stress on the density of mud density varies for the samples collected from European ports. As an example, fluidic yield stress values are plotted as a function of density for the samples collected from different ports (see Figure 2). One observes that the mud samples obtained from different ports exhibit considerably different yield stress values for a particular density. This difference may be attributed to the composition of mud, particle size distribution, type of clay, type and content of total organic carbon (TOC) and ionic strength. This behaviour highlights the needs for a systematic investigation of the rheological properties of mud, as function of relevant parameters, for different ports.

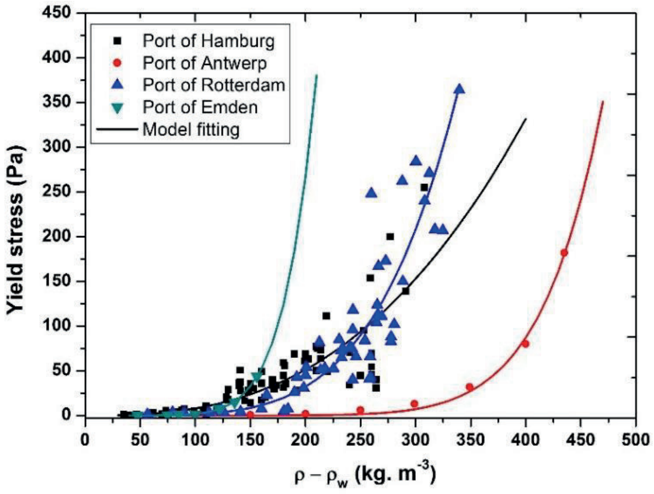

Figure 2. Fluidic yield stress as a function of the excess density ($\rho - \rho_w$; with ρ = bulk density and ρ_w = density of water) for mud from different European ports (Shakeel et al., 2021a)

Density is an important characteristic of mud which can significantly affect its rheological properties, such as yield stress, thixotropy and moduli. In natural environments, the density gradient in mud is usually created by natural sediment deposition and consolidation and can be influenced by human interventions such as maintenance dredging and navigation. Typically, the rheological characteristics of mud as a function of density are reported either for natural mud layers with varying density (Shakeel et al., 2020a) or for dilutions of dense mud samples (Van Kessel and Blom, 1998; Huang and Aode, 2009). However, it has been observed that the natural and diluted mud layers display significantly different rheological properties (see Figure 3), which may again be linked to the composition of each mud layer or dilution protocol (Shakeel et al., 2020b).

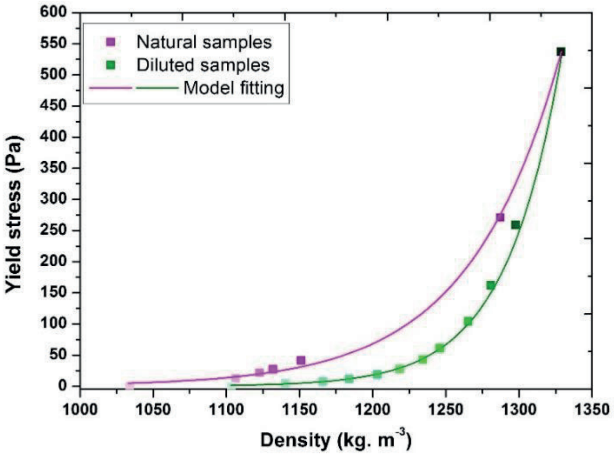

Figure 3. Fluidic yield stress values versus bulk density for natural and diluted mud layers from Port of Hamburg. Solid lines represent the power law fitting (Shakeel et al., 2020b)

The correlation between yield stress and density is highly dependent on the mud composition. For example, the (fluidic) yield stress values as a function of density for mud samples collected from different locations of port of Hamburg is shown in Figure 4a. It can be seen that the dependence of yield stress on mud density is significantly different for the samples collected at different locations, even within the same sedimentary system (port). In order to further quantify this difference, both the fitting parameter ‘a’ for the power law relation given in Figure 6a and the TOC content are plotted as function of different locations along an upstream (L1) - downstream (L10) gradient (Figure 4b). The correlation between the TOC and the fitting parameter ‘a’ suggests that the yield stress of mud strongly depends on both, density and organic carbon content, as already reported in literature (Wurpts and Torn, 2005; Shakeel et al., 2019). The spatial gradient with decreasing organic carbon content and decreasing values for the fitting parameter ‘a’ align with a spatial gradient of decreasing organic matter degradability (Zander et al., 2020). High TOC contents and values for ‘a’ at L1 and L2 also mirror the enhanced supply of labile, planktonic biomass input to upstream locations suggested by high chlorophyll a and silicic acid concentrations in the water column.

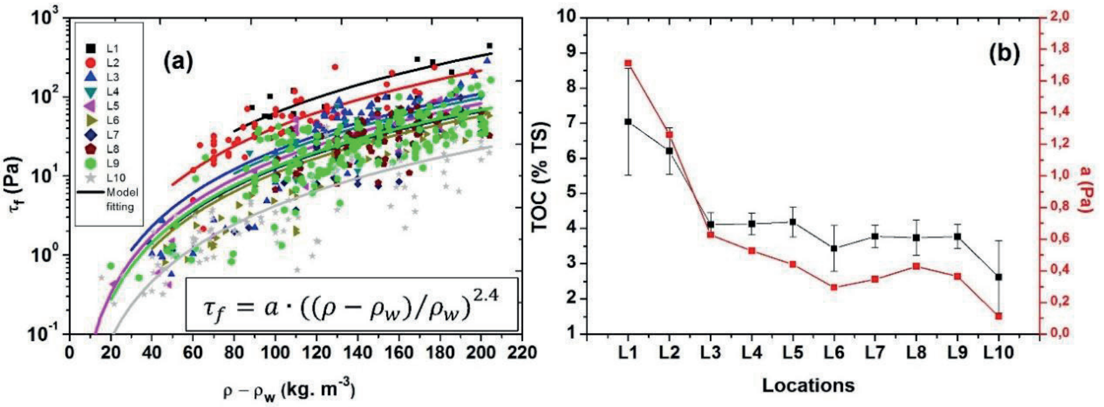

Figure 4. (a) Fluidic yield stress as a function of excess density $(\rho - \rho_w)$ for mud samples from different locations in the Port of Hamburg. The solid lines represent the power law fitting with one fitting parameter ‘a’. ρ_w represents the density of water. L1 to L10 represent the locations from upstream to downstream locations in the Port of Hamburg. (b) fitting parameter ‘a’ and TOC as a function of different locations of Port of Hamburg (Shakeel et al., 2021b)

2.3 Settling behavior of mud

The link between settling and density has been studied in depth (Richardson and Zaki, 1954; Chassagne, 2020). Kaolinite suspensions are known to have fast settling behaviour and Newtonian character at low concentrations due to the non-swelling nature of their constitutive particles. On the other hand, montmorillonite and bentonite are known for their swelling and interacting nature, which leads to the formation of a network structure even at low concentrations. Figure 5a shows a series of settling experiments conducted with clays mixtures containing three clays (kaolinite, illite and bentonite) with varying fraction of bentonite with regards to the total solid content that is kept constant (15 wt%). Due to increased repulsion between negatively charged clay particles settling of samples containing a higher fraction of bentonite was slower in comparison with samples without bentonite. Patterns created by settling illite particles also confirms, that bentonite can trap particles of kaolinite and illite and stabilize a structure with high amount of void spaces. Patterns were not visible for the control sample and they disappeared when the bentonite content exceeded 5 wt.% (see photos in Figure 5b).

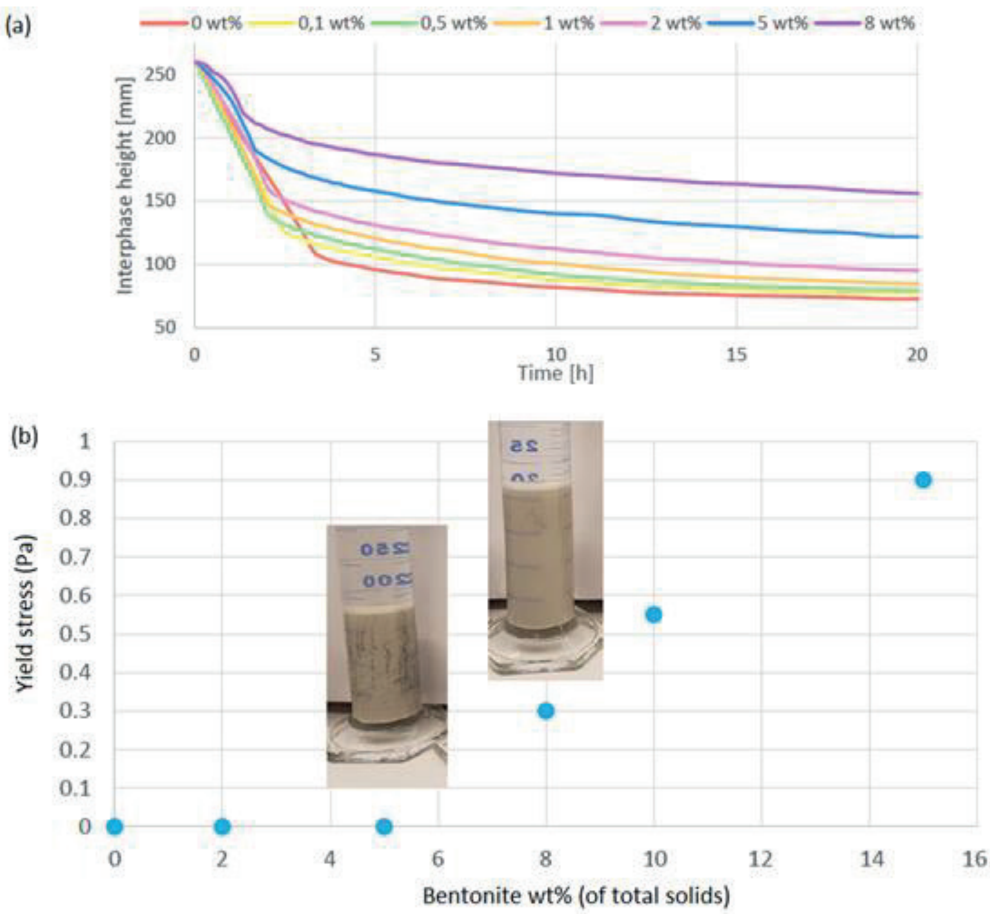

Figure 5. Settling (a) and yield stress (b) tests on mixtures containing three clays (kaolinite, illite and bentonite) with 0 wt%, 0.1 wt%, 0.5wt%, 1 1 wt%, 2 wt%, 5 wt% and 8 wt% of bentonite in total solids

Comparison of the rheological behaviour (yield stress) between samples confirmed that the critical concentration of bentonite, which results in increased yield stress, is between 5 wt.% and 8 wt.% (see Figure 5b). Increased yield stress was observed for sample containing 8 wt.% of total solids of bentonite. This amount represents only 1.20 wt.% of the total sample and proves, that despite very low amounts, swelling clays dominates the behaviour of the clay mixture.

Settling column analysis and yield stress measurements were also performed for the mixed suspensions bentonite/kaolinite suspensions (see Shakeel et al., 2021c for details). The yield stress (determined from the viscosity decline and second yield point in case of systems with two-step yielding) is then plotted as a function of kaolinite/bentonite fraction for different total solid content (Figure 6a). The measurements are consistent with the ones in Figure 5b as the yield stress increases with an increasing fraction of bentonite.

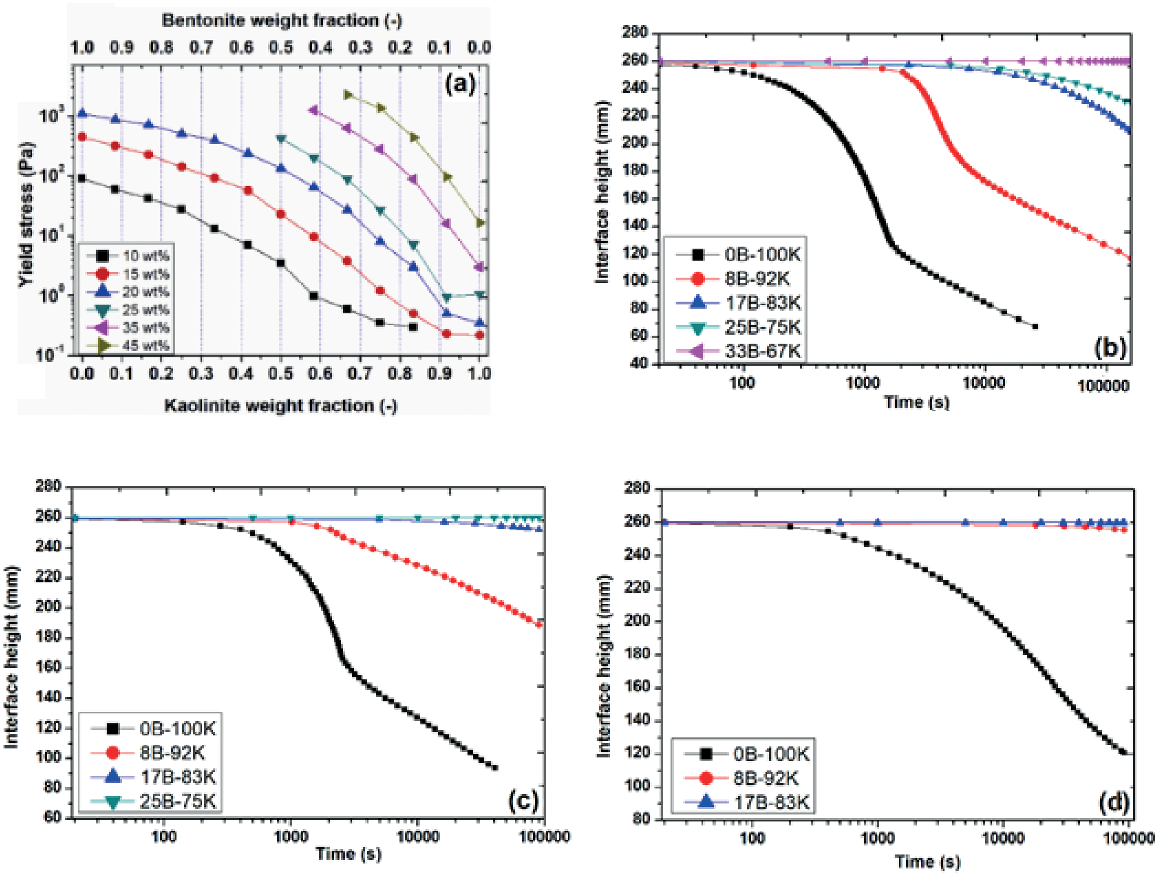

Figure 6. Settling column experiments with varying ratios of kaolinite/bentonite. (a) Measured yield stress of varying kaolinite/bentonite weight fractions. Clay/water interface heights as a function of time for suspensions having (b) 10 wt%, (c) 15 wt%, and (d) 20 wt% total solid content with varying ratios of kaolinite/bentonite (Shakeel et al. 2021c)

Figures 6b-6d show the results of settling columns tests on a clay suspension having different total solid content and varying kaolinite/bentonite fractions. It was confirmed that a very small amount of bentonite was needed to stabilize the kaolinite suspensions without adding any significant amount of salt or organic matter. This result verified that the sample having no yield stress showed significant settling behaviour while the stabilized suspension displayed the existence of the yield stress.

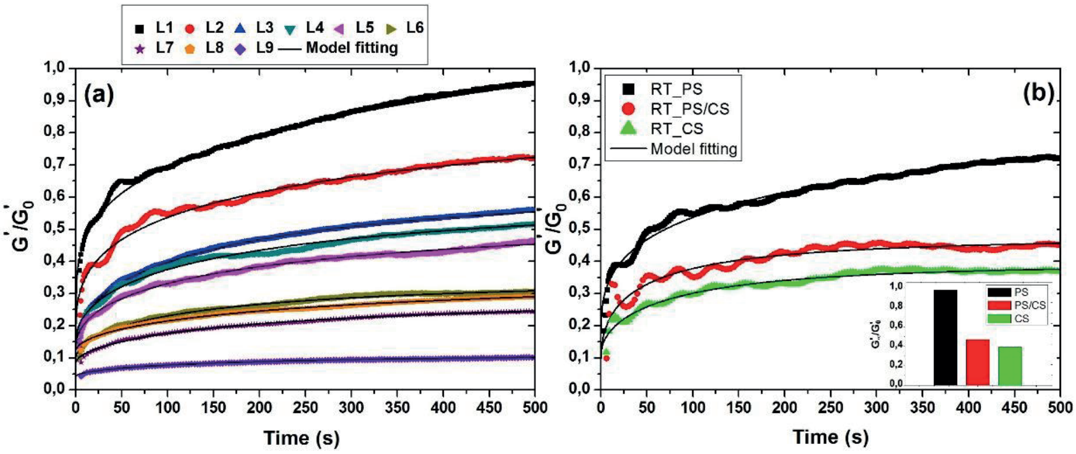

Figure 7. (a) Normalized storage modulus (G'/G'_0) as a function of time for pre-consolidated (PS) sediment sampled at different locations of Port of Hamburg and pre-sheared at 100 s^{-1} using Couette geometry. L1 to L10 represent the locations from upstream to downstream in the Port of Hamburg, where the samples with similar densities were collected. (b) normalized storage modulus (G'/G'_0) as a function of time for different mud layers having different densities collected from one location of Port of Hamburg and pre-sheared at 100 s^{-1} using Couette geometry. Inset shows the equilibrium structural parameter (G'_∞/G'_0) for different mud layers (Shakeel et al. 2020c). CS = consolidated sediment, RT = sampling location 'Rethe'

2.4 Structural recovery

Apart from yield stress, other rheological properties including moduli, thixotropy, structural recovery exhibit a strong dependency on the density of mud (Shakeel et al., 2020c, b). For instance, the structural recovery, observed by a three step protocol, for mud collected from different locations and different depths of Port of Hamburg is shown in Figure 7a and 7b, respectively. The measurements confirm that the structural recovery (i.e., moduli values) of mud is highly dependent on the mud layer, and sampling location in the harbour (Shakeel et al., 2020c). Hence, density of mud is a critical parameter particularly for describing its rheological characteristics, however, selecting the density as a physical characteristics of the bottom for the nautical bottom approach in ports is not enough and other parameters also require attention.

2.5 Organic matter content and degradation

The presence of organic matter in mud usually hinders the settling of sediment particles and can help to form fluid mud layers. This organic matter can or cannot be mineral-associated organic matter (i.e., organic matter adsorbed at the mineral surface or trapped inside the particle) (Hedges and Keil, 1999). There are two common sources of organic matter in mud: (i) natural and (ii) anthropogenic. The natural sources include erosion of terrestrial topsoils, plant litter, planktonic and pelagic biomass while surface runoff and sewage waste contribute to the anthropogenic source of organic matter.

Organic matter in mud has a significant influence on the rheological properties of mud (Wurpts and Torn, 2005; Malarkey et al., 2015; Schindler et al., 2015). For instance, when varying organic matter content but keeping density constant (Shakeel et al., 2019), yield stress and moduli increased with increasing organic matter content (see Figure 8a). However, further research is required to investigate the multifactorial effects of variable type of organic matter/biopolymer, different pH, and ionic concentrations on the rheological behaviour of mud.

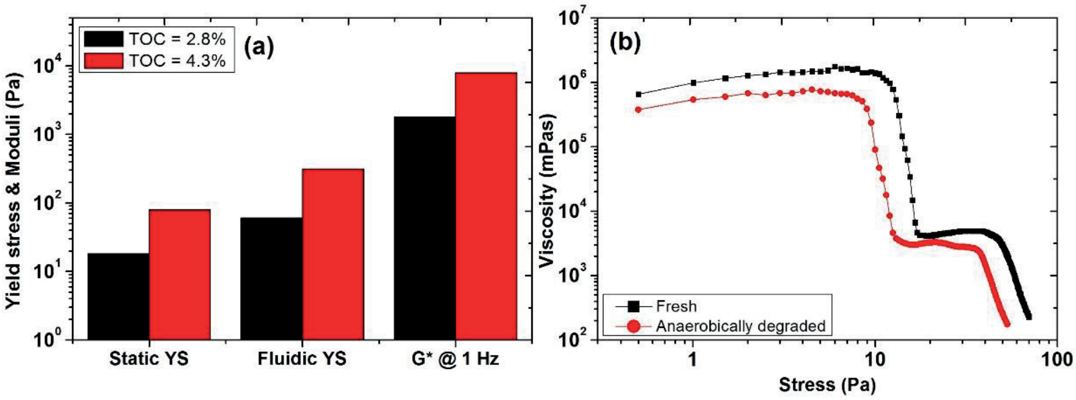

Figure 8. (a) Yield stress values and complex modulus at 1 Hz for mud samples having similar density (1210 kg. m^{-3}) and different organic matter content obtained from Port of Hamburg, (Shakeel et al., 2019) (b) apparent viscosity as a function of shear stress for fresh and anaerobically degraded mud samples obtained from Port of Hamburg

In addition to organic matter content, its extent of degradation can also significantly affect the rheological properties of mud. Aerobic degradation (in the presence of oxygen) of organic matter usually results in the production of carbon dioxide while anaerobic degradation produces methane in addition to carbon dioxide (Zander et al., 2020). The entrapped gas bubbles of methane can significantly decrease the density and strength of mud, due to the poor solubility of methane in water. The outcome of stress ramp-up tests for fresh and anaerobically degraded mud samples, collected from Port of Hamburg, is shown in Figure 8b. It can be seen that the values of the two yield stresses (static and fluidic) for the degraded sample are significantly lower than the fresh ones. This decline is hypothesized to be due to the microbial breakdown of organic bridges between mineral particles. However, further quantification of organic matter content before and after degradation is required, in order to correlate the organic matter degradation with rheological characteristics of mud.

The influence of anaerobic degradation of organic matter on the yield stresses of mud samples from different European ports is presented in Figure 9 in terms of change in static or fluidic yield stresses (degraded – fresh) as a function of yield stress of fresh samples. The experimental data was fitted by using an empirical relation given as $y = a + bx$, where a and b represent the intercept and slope of the line, respectively. The fitting lines in Figure 9 indicate that the yield stresses were significantly decreased for mud samples from Port of Antwerp (PoA) and

Port of Hamburg (PoH). In case of mud samples from Port of Rotterdam (PoR), the reduction in yield stresses was less significant. On the other hand, the mud from Port of Emden (PoE) exhibited a slight increase in yield stress values after microbial degradation, which may be related to the specific maintenance strategy in Port of Emden (i.e., recirculation), resulting in fluid mud of very low yield stresses and presumably a large degree of stabilization of the organic matter. This analysis further verifies that even the influence of organic matter degradation on the rheological properties of mud is significantly different for different ports.

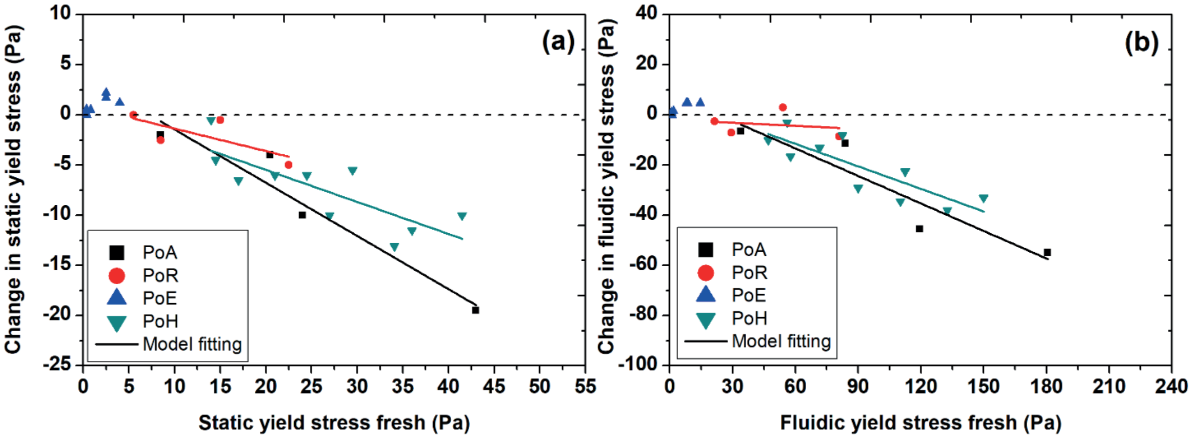

Figure 9. Change in static yield stress (degraded – fresh) as a function of static yield stress of fresh mud samples and (b) change in fluidic yield stress (degraded – fresh) as a function of fluidic yield stress of mud from Port of Antwerp (PoA), Port of Rotterdam (PoR), Port of Emden (PoE) and Port of Hamburg (PoH). The solid line shows the empirical linear fitting

2.6 Correlation between laboratory and in-situ rheological measurements

Figure 10 shows the comparison of the yield stress values measured in-situ and in laboratory as a function of density at different locations of the Port of Hamburg. The in-situ measurements for Vorhafen (VH) and for Köhlfleet mit Köhlfleethafen (KH) match well with the laboratory experiments. However, the values measured for Rethe (RT) and Reiherstieg Vorhafen (RV) showed the smaller in-situ yield stress compared with the one measured in the laboratory. The discrepancy can be due to high organic matter content in RT and RV (Shakeel et al., 2020a).

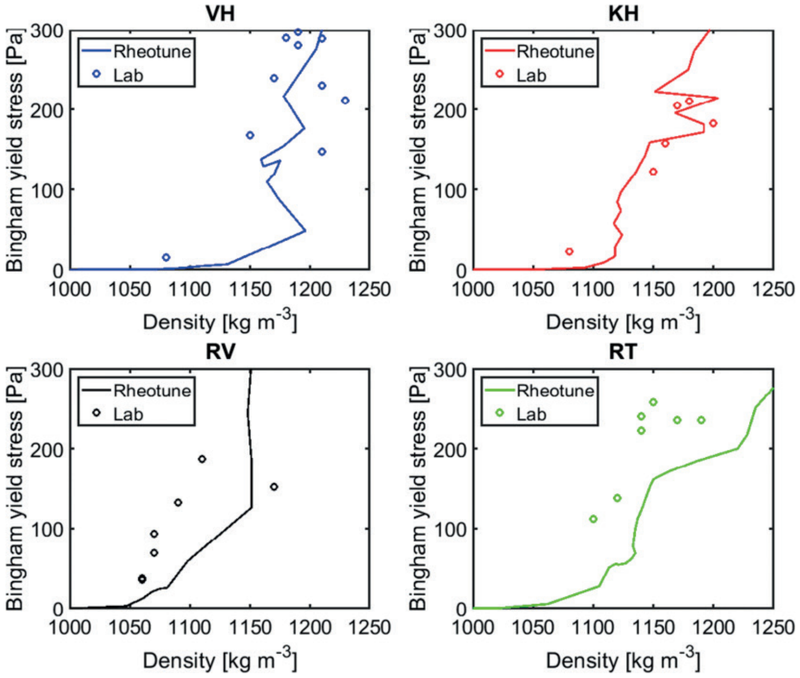

Figure 10. Comparison of densities and yield stresses measured in-situ using the Rheotune and in laboratory using the Couette rheometer. The abbreviations indicate different locations in the Port of Hamburg: Vorhafen (VH), Köhlfleet mit Köhlfleethafen (KH), Rethe (RT) and Reiherstieg Vorhafen (RV) (Kirichek et al., 2020)

The Rheotune and the Graviprobe have also been tested in the Port of Rotterdam (Kirichek and Rutgers, 2020). Figure 11 shows the corresponding densities and yield stress measurements from Rheotune. The in-situ densities were measured using Rheotune and the Anton Paar density meter combined with Slibsampler. The yield stress was measured in-situ and in the laboratory by Rheotune and the HAAKE MARS I rheometer, respectively. It is found that the Rheotune and Slibsampler density data are in very good agreement, as is the yield stress data found by Rheotune and rheological measurements in the lab. The reason for the better agreement, than for the experiments conducted in the Port of Hamburg, is most probably related to the lower amounts of organic matter content in the Port of Rotterdam.

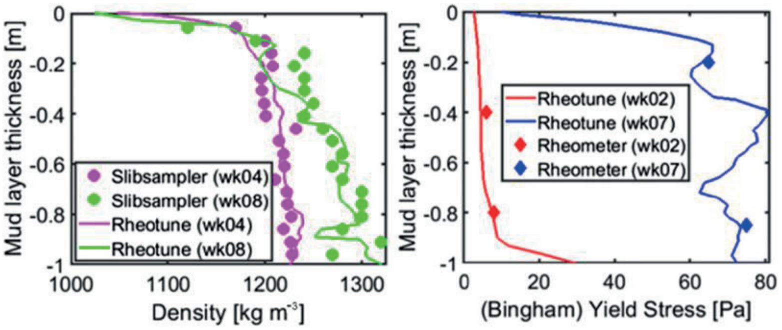

Figure 11. Validation of density and yield stress values measured by Rheotune in the Port of Rotterdam at the sediment trap after water injection dredging. Wk02 = after 2 weeks, wk04 = after 4 weeks, wk07 = after 7 weeks and wk08 = after 8 weeks (Kirichek et al. 2020)

3 CONCLUSION

Settling and rheological behaviour of mud from different European ports has been extensively studied for the nautical bottom and port maintenance purposes over the last years. Currently-available laboratory protocols for measuring rheological properties have been compared. Robust and reliable rheological protocols for measuring the yield stresses and structural recovery of mud have been identified. Variation of yield stress values in different ports has been studies by identifying the link between rheological properties and other key sediment properties of mud like density, mud composition, clay content and clay type, settling, TOC and organic matter degradation in-situ and in the laboratory. New generated knowledge on rheology and settling of mud in ports has been shared with dredging engineering community via open-source scientific and technical papers.

ACKNOWLEDGEMENTS

This study is funded by the Hamburg Port Authority and carried out within the framework of the MUDNET academic network: https://www.tudelft.nl/mudnet/. The authors would like to acknowledge Deltares (the Netherlands) for the use of the HAAKE MARS I rheometer, which was made possible thanks to the Memorandum of Understanding signed between Deltares and the TU Delft.

REFERENCES

Chassagne C. (2019). Introduction to Colloid Science: Applications to sediment characterization. *Delft Academic Press (DAP)*, Delft, SBN: 97890-6562-4376.

Claeys S., Staelens P., Vanlede J., Heredia M., Van Hoestenberghe T., Van Oyen T. & Toorman E. (2015): A rheological lab measurement protocol for cohesive sediment. *INTERCOH2015. Book of Abstracts*

Buisman M., Martuganova E., Kiers T., Draganov D. & Kirichek A. (2022). Continues bathymetry measurements using Distributed Acoustic Sensing: Measuring standing waves for depth estimations. *Journal of Soils and Sediments*.

Hedges J.I. & Keil R.G. (1999). Organic geochemical perspectives on estuarine processes: sorption reactions and consequences. *Marine chemistry,* Vol. 65, 55-65.

Huang Z. & Aode H. (2009). A laboratory study of rheological properties of mudflows in Hangzhou Bay, China. *International Journal of Sediment Research*, Vol. 24, 410-424.

Kirichek A., Chassagne C., Winterwerp H. & Vellinga T. (2018). How navigable are fluid mud layers? *Terra et Aqua,* Vol. 151, 6-18.

Kirichek A., Shakeel A. & Chassagne C. (2020). Using in situ density and strength measurements for sediment maintenance in ports and waterways. *Journal of Soils and Sediments*, Vol. 20, 2546-2552.

Kirichek A. & Rutgers R. (2020). Monitoring of settling and consolidation of mud after water injection dredging in the Calandkanaal. *Terra et Aqua,* Vol. 160, 16-26.

Malarkey J., Baas J.H., Hope J.A., Aspden R.J., Parsons D.R., Peakall J., Paterson D.M., Schindler R.J., Ye L., Lichtman I.D., Bass S.J., Davies A.G., Manning A.J. & Thorne P.D. (2015). The pervasive role of biological cohesion in bedform development. *Nature Communications,* Vol. 6, 6257.

PIANC (2014). Harbour Approach Channels - Design Guidelines, Report 121, *PIANC*, Brussels.

Richardson J.F. & Zaki W.N. (1954). The sedimentation of a suspension of uniform spheres under conditions of viscous flow. *Chemical Engineering Science*, Vol. 3, No. 2, 65-73.

Schindler R.J., Parsons D.R., Ye L., Hope J.A., Baas J.H., Peakall J., Manning A.J., Aspden R.J., Malarkey J., Simmons S., Paterson D.M., Lichtman I.D., Davies A.G., Thorne P.D. & Bass S.J. (2015). Sticky stuff: Redefining bedform prediction in modern and ancient environments. *Geology,* Vol. 43, 399-402.

Shakeel A., Kirichek A. & Chassagne C. (2019). Is density enough to predict the rheology of natural sediments? *Geo-Marine Letters*, Vol. 39, 427-434.

Shakeel A., Kirichek A. & Chassagne C. (2020a). Rheological analysis of mud from Port of Hamburg, Germany. *Journal of Soils and Sediments*, Vol. 20, 2553-2562.

Shakeel A., Kirichek A. & Chassagne C. (2020b). Rheological analysis of natural and diluted mud suspensions. *Journal of Non-Newtonian Fluid Mechanics*, Vol. 286, 104434.

Shakeel A., Kirichek A. & Chassagne C. (2020c). Effect of pre-shearing on the steady and dynamic rheological properties of mud sediments. *Marine and Petroleum Geology*, Vol. 116, 104338.

Shakeel A., Kirichek A. & Chassagne C. (2021a). Rheology of Mud: An Overview for Ports and Waterways Applications. *IntechOpen.*

Shakeel A., Kirichek A. & Chassagne C. (2021b). Rheological analysis and rheological modelling of mud sediments: What is the best protocol for maintenance of ports and waterways? *Estuarine, Coastal and Shelf Science,* Vol. 257, 107407.

Shakeel A., Kirichek A. & Chassagne C. (2021c). Rheology and yielding transitions in mixed kaolinite/bentonite suspensions. *Applied Clay Science*, Vol. 211, 106206.

Van Kessel T. & Blom C. (1998). Rheology of cohesive sediments: comparison between a natural and an artificial mud. *Journal of Hydraulic Research*, Vol. 36, 591-612.

Wurpts R. & Torn P. (2005). 15 years experience with fluid mud: Definition of the nautical bottom with rheological parameters. *Terra et Aqua*, Vol 99, 22-32.

Xu J. & Huhe A. (2016). Rheological study of mudflows at Lianyungang in China. *International Journal of Sediment Research,* Vol. 31, 71-78.

Yang W., Yu G., Tan S. & Wang H. (2014). Rheological properties of dense natural cohesive sediments subject to shear loadings. *International Journal of Sediment Research*. Vol. 29, 454-470.

Zander F., Heimovaara T. & Gebert J. (2020). Spatial variability of organic matter degradability in tidal Elbe sediments. *Journal of Soils and Sediments*, Vol. 20, 2573-2587.