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An Overview for Ports and Waterways Applications

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Chapter

Rheology of Mud: An Overview for Ports and Waterways Applications

Ahmad Shakeel, Alex Kirichek and Claire Chassagne

Abstract

Mud, a cohesive material, consists of water, clay minerals, sand, silt and small quantities of organic matter (i.e., biopolymers). Amongst the different mud layers formed by human or natural activities, the fluid mud layer found on top of all the others is quite important from navigational point of view in ports and waterways. Rheological properties of fluid mud layers play an important role in navigation through fluid mud and in fluid mud transport. However, the rheological properties of mud are known to vary as a function of sampling location within a port, sampling depth and sampling location across the globe. Therefore, this variability in rheological fingerprint of mud requires a detailed and systematic analysis. This chapter presents two different sampling techniques and the measured rheological properties of mud, obtained from laboratory experiments. The six protocols used to measure the yield stresses are detailed and compared. Furthermore, the empirical or semi-empirical models that are commonly used to fit rheological experimental data of such systems are presented. The influence of different factors such as density and organic matter content on the rheological behavior of mud is discussed. The fluidic yield stress of mud samples was observed to vary from 0.2 Pa to 500 Pa as a function of density and organic matter content.

Keywords: Mud, rheology, density, yield stress, moduli, flow curve, protocol, organic matter, nautical bottom, cohesive sediment

1. Introduction

Mud beds, typically found at the bottom of rivers, lakes and in coastal areas, belong to the category of cohesive material. These deposits consist of water, clay minerals, sand, silt and organic matter (such as living microorganisms and in particular their excreted biopolymers) [1]. These mud beds are usually exposed to a continuous wave motion and disturbances produced by ship movement [1, 2], human actions such as dredging [3], natural climatic events and bioturbation [4]. The water column can be divided into different layers. In its large upper part, where mud particles are advected by currents and diffused by turbulent motion, mud is found as suspended particulate matter (SPM). Close to the bottom, different mud layers are found with increasing density as function of depth. These layers are defined as fluid mud (FM), pre-consolidated sediment (PS) and consolidated sediment (CS). Besides having different densities, these mud layers are known to have significantly different compositions and rheological fingerprints.

Fluid mud, the most important mud layer from a navigational perspective, is typically identified as a layer with a density of 1030–1300 kg m^{-3}, whereby hindered settling of particles plays a role due to the presence of flocs (i.e., combination of clay particles and organic matter) [5–7]. All mud layers, but particularly the fluid mud layer, display complex rheological behavior, i.e., combination of thixotropy, shear-thinning, two-step yielding behavior and viscoelasticity [8, 9]. The rheological/cohesive properties of mud are observed to vary as a function of solid fraction (or bulk density), type and concentration of organic matter, type of clay minerals and ionic concentration [10–17]. The thorough understanding of the rheological characteristics of mud, as a function of above-mentioned parameters, can help to estimate the strength, the flow and thickness of (fluid) mud in ports and waterways. The quantification of the rheological properties for fluid mud also facilitates the definition of boundary conditions for sediment transport modeling, which in turn helps optimizing the dredging operations and defining the proper maintenance strategy for navigational channels [18–21]. However, in order to develop the appropriate in-situ techniques for measuring rheological properties, these characteristics need to be analyzed in laboratory beforehand. Therefore, in this chapter, following research questions are answered: How to efficiently collect the "undisturbed" mud sample? Which sediment properties are important for determining the rheological properties of mud? Which protocols are suitable for measuring rheological characteristics, i.e., yield stress of mud? Which empirical or semi-empirical model is appropriate to fit the rheological experimental data of mud, particularly for two-step yielding? How much comparable is the rheological signature of mud samples from different sources?

In this chapter, two different sampling techniques are presented to collect the "undisturbed" mud samples along with their important physical properties (Section 2). In Section 3, different protocols used to measure the rheological properties particularly yield stresses of mud are detailed and compared. Furthermore, the empirical or semi-empirical models that are commonly used to fit the rheological experimental data of mud are presented in Section 4. The influence of different factors such as density and organic matter content on the rheological behavior of mud is discussed in Section 5. In the end, the rheological properties, i.e., yield stress, of mud samples obtained from different ports are compared. In the present chapter, only laboratory experiments are presented.

2. Sampling techniques and physical properties of mud

In order to determine the physical and rheological characteristics of mud in the laboratory, appropriate sampling method needs to be applied. Two of the most commonly used sampling methods/equipment for mud are: (i) Van Veen grab sampler, and (ii) Frahmlot core sampler (see **Figure 1**). The criterion for selecting the suitable sampling method is based on the fact that the mud should be obtained in an "undisturbed" state with a naturally occurring density gradient profile, in order to estimate the properties of mud as close as possible to in-situ conditions. Core sampler is considered to meet this criterion well. Apart from collecting in-situ mud layers with different densities, another approach to study the effect of density on the rheological behavior is to dilute a consolidated mud layer, to obtain different samples with varying densities [9, 23]. However, the rheological characteristics of natural and diluted mud layers of same density are found to vary significantly from each other [24].

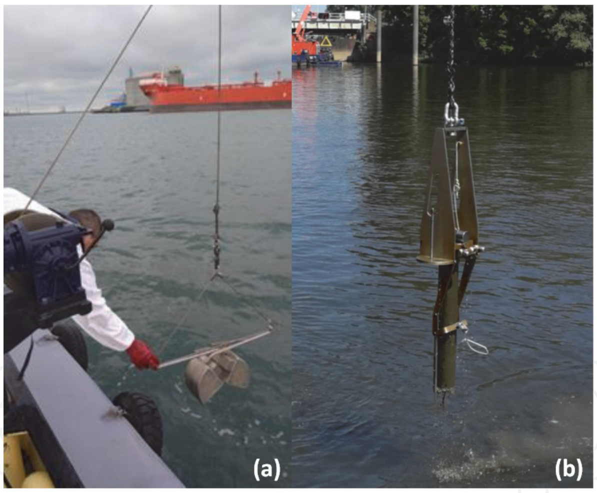

Figure 1.
(a) Van Veen grab sampler and (b) Frahmlot core sampler [22].

The bulk density (or water content) of the mud samples is usually estimated using the oven-drying method [25–28]. In short, the weight of the sample is recorded before and after heating at 105°C for 24 h. Using these weights and the density of water and minerals (i.e., 1000 and 2650 kg m^{-3}, respectively), the mean bulk density of the sample is obtained. The particle size distribution (PSD) of mud is typically investigated using (static) light scattering methods [17, 28, 29]. However, this technique also possesses some inherent drawbacks which are the facts that (i) the conversion between raw data and particle size is based on the assumption that the particles are spherical and have a homogeneous composition, (ii) the measurements are possible in a limited range of concentrations, and (iii) there can be a serious overestimation of the amount of large particles due to the mathematical smoothing of the PSD's by the manufacturer's software [30]. The total organic carbon (TOC) of mud samples is commonly analyzed by using loss-on-ignition method [31, 32], which is based on weighing the sample before and after heating at 430–500°C for 24 h. The total organic carbon is then estimated by loss in weight. All these sediment properties are known to significantly influence the rheological characteristics of mud samples.

3. Protocols for measuring rheological properties of mud

3.1 Yield stress

Mud can either behave as a solid-like material (i.e., elastic solid) at small stresses or as a liquid-like material above a critical value of stress, defined as yield stress. The nautical bottom for ports and waterways is typically defined on the basis of mud density [33], which does not account for the solid/liquid transition defined by the yield stress. Measurement of the yield stress of mud is, therefore, quite useful in defining the navigability of mud layers [15, 21]. The determination of yield stress is highly dependent on the selected rheological geometry and experimental method, as significantly different yield stress values can be obtained due to (i) the history of samples before analysis, (ii) differences in experimental methods, (iii) the use of different criteria for defining the yield point, (iv) different experimental timescales [34–39].

Several rheological geometries are available to perform the rheological analysis of mud including concentric cylinder (Couette), cone & plate (CP), parallel plate (PP) and vane. Cone & plate geometry has been observed to produce scattered rheological responses for mud samples due to the presence of large particles within the narrow gap between cone and plate and, hence, is not recommended for this kind of samples [40]. The remaining geometries can be used for analyzing mud samples but with certain benefits and limitations for each one. The differences between the geometries is illustrated in **Figure 2a** which shows the response of a FM mud layer in terms of elastic stress ($= G'\gamma$) as a function of applied oscillatory amplitude at 1 Hz for different geometries. It can be clearly seen that the mud sample exhibits a two-step yielding behavior (i.e., two distinct peaks in the response of elastic stress). The associated yield stresses are termed as “static” and “fluidic” yield stresses, and their values and dependence on amplitude are function of the used geometry. These two characteristic yield points can be associated to the breaking of floc network, re-organization and breakdown of flocs during shearing [40–43].

Figure 2b presents the yield stress values of different mud layers obtained by using the elastic stress method for different geometries. The results show that the highest yield stress values are obtained for parallel plate geometry, which may be attributed to the fact that this geometry induces the lowest disturbance in the sample while the plates are approached to confine the sample. However, this geometry is not very appropriate for analyzing the rheology of liquid-like samples, as the sample can flow out of the holder during shearing. Couette geometry is most suitable to analyze the rheological characteristics of mud ranging from very fluid to paste-like. For consolidated samples, however, it is preferable to use vane geometry, as the bob used in Couette geometry usually gets stuck during analysis of (very) dense mud samples.

In addition to different geometries, several rheological protocols have been reported in literature to determine the yield stress of mud. These protocols include shear rate ramp-up [29, 44], shear stress ramp-up [15, 17], and Claeys et al. protocol [45]. Shear rate/shear stress ramp-up methods are quite fast and easy to perform. On the other hand, Claeys et al. protocol is based on several cycles of selected shear rates (applying a shear, stop shearing, applying a shear …) along with high shear rate steps in-between these cycles, with a total experimental time of about 15–20 min. **Figure 3** shows the pictorial representation of different experimental protocols that can be used to measure the yield stresses of mud.

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 4**. The values of yield stresses (static and fluidic) obtained

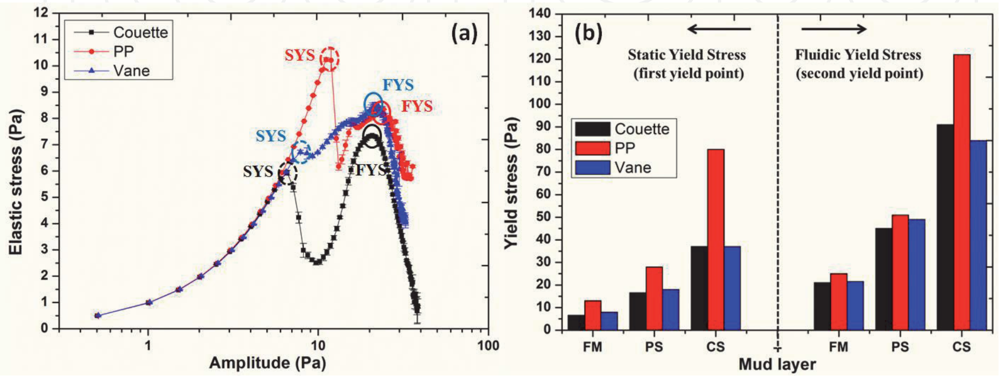

Figure 2.

(a) Elastic stress as a function of amplitude at 1 Hz using different geometries for FM layer obtained from Port of Hamburg. Solid line is just a guide for the eye. Bars represent standard deviation. Circles with dashed lines represent the static yield points (SYS) and circles with solid lines represent the fluidic yield points (FYS). (b) Static and fluidic yield stress values obtained from elastic stress method for different mud layers collected from Port of Hamburg using Couette, parallel plate and vane geometries. Reprinted from Ref. [40].

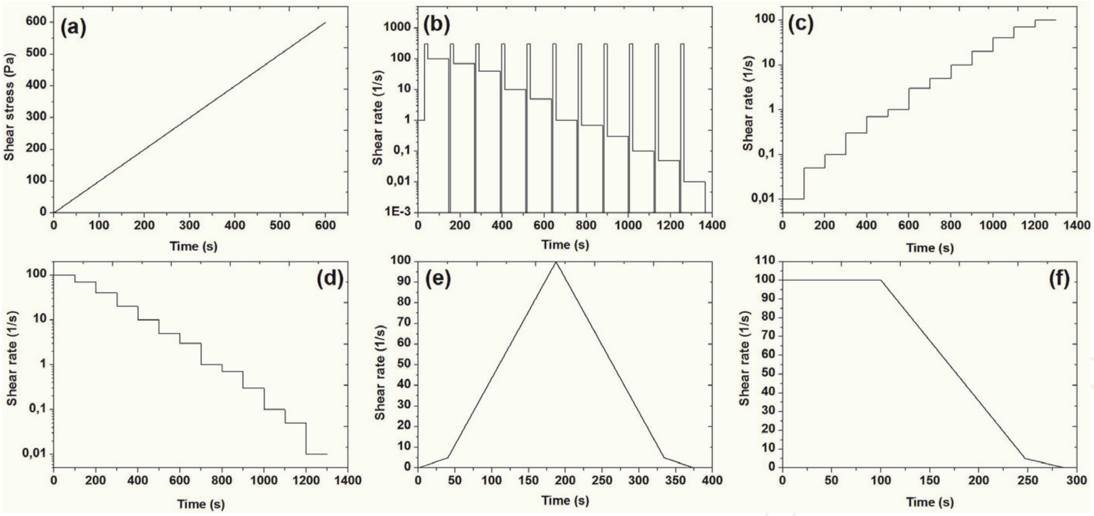

Figure 3.
Pictorial representation of the protocols (a) stress ramp-up, (b) Claeys et al. protocol, (c) increasing equilibrium flow curve (EFC), (d) decreasing equilibrium flow curve (EFC), (e) shear rate ramp up and ramp down (CSRT) and (f) pre-shear test. Reprinted from Ref. [46].

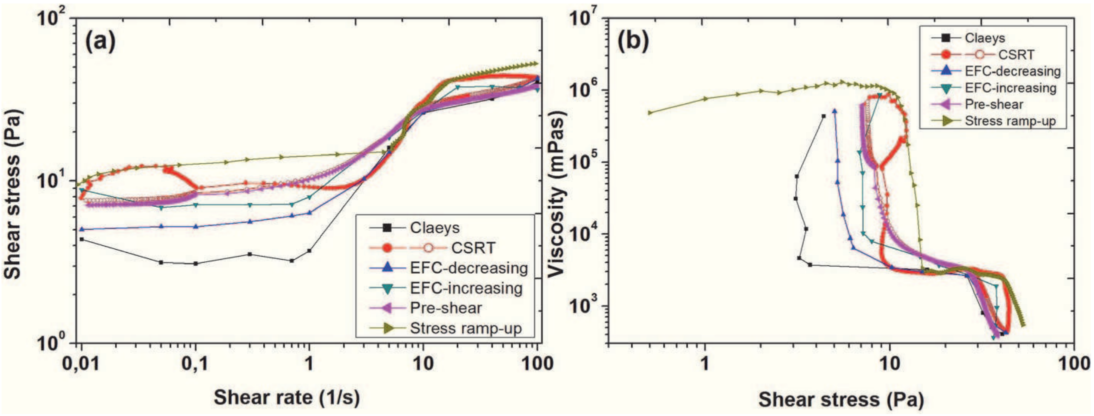

Figure 4.
(a) Shear stress as a function of shear rate and (b) apparent viscosity as a function of shear stress for mud sample collected from port of Hamburg using Couette geometry; solid symbols in CSRT protocol represent the ramp-up and the empty symbols represent the ramp-down; solid lines are just the guide for the eye. Reprinted from Ref. [46].

Method	Static Yield Stress (Pa)	Fluidic Yield Stress (Pa)
Claeys 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

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.

from the viscosity declines of these curves (see **Figure 4b**) are presented in **Table 1**. 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 somehow difficult in case of ramp-up step of CSRT test (due to the scattering of the initial apparent viscosity as function of stress points, see black curve in **Figure 4b**) and increasing EFC test is a somehow lengthy test (∼ 20 min, see **Figure 3c** and **d**). Therefore, it is recommended to use stress ramp-up test for analyzing the 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 quite lower, which indicates the extensive structural breakdown of the samples during analysis.

In literature, several terminologies have been used to represent the two yield points for mud. The correspondence between these terminologies is presented in **Table 2**.

3.2 Thixotropy and structural recovery

Thixotropy, a commonly observed rheological fingerprint of suspensions, is defined as a phenomenon in which the viscosity of the system is both shear rate and time dependent. Therefore, a thixotropic material shows a time dependent viscosity (decreasing as a function of time; when the viscosity is increasing as a function of time the material is said to be rheopectic) after applying/stopping shear rate [49]. Typically, the thixotropic behavior of mud is determined by performing a shear rate ramp-up followed by a constant high shear step and then a shear rate ramp-down step [17, 44]. The area of the hysteresis loop formed between the upward and downward curve quantifies the thixotropic behavior of the material [50]. Multiple thixotropic loops can also be produced for the same sample without allowing for any delay between each loop, in order to understand the thixotropic behavior of mud after extensive structural breakdown [17].

In addition to thixotropy, the structural recovery of mud after extensive shearing is also interesting to analyze by using small amplitude oscillatory rheological measurements. A three step experimental protocol has been reported in literature to quantify the structural recovery of mud after steady pre-shearing [51]. In short, the first step of the protocol involves the application of an oscillatory amplitude within the linear viscoelastic (LVE) regime and recording the moduli as a function of time (i.e., resting step). This step provides the initial moduli values before the pre-shearing step and also eliminates the disturbances created by the geometry. In a second step, a constant high shear rate is applied for a time interval which is enough to completely destroy the structure of the sample (i.e., pre-shear step). The last step provides the key information about the structural recovery of mud after

Shakeel et al. [17]	**Toorman** [47]	**Toorman** [48]	**Wurpts & Torn** [15]	**Claeys et al.** [45]
Fluidic yield stress		Static yield stress	Criterion for navigation	Undrained shear strength
ΔYS = (Fluidic – Static)	Bingham yield stress	Dynamic yield stress		Bingham yield stress
Static yield stress	(True) yield stress		Yield stress	

Table 2.
Correspondence between different yield stress terminologies reported in literature for mud.

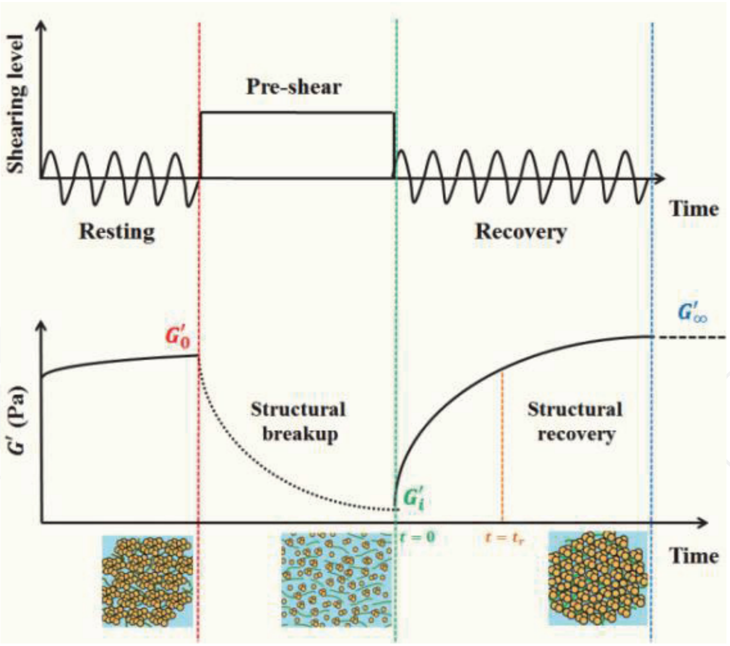

Figure 5.
Schematics of the experimental protocol employed for the structural breakup and recovery in mud samples. Reprinted from Ref. [51].

pre-shearing, again by applying the oscillatory amplitude within LVE regime and recording the moduli as a function of time (i.e., structural recovery step). The schematic representation of the experimental protocol is shown in **Figure 5**.

3.3 Moduli

Apart from above mentioned rheological properties of mud, the estimation of moduli (storage and loss) within LVE regime (i.e., without significantly affecting the structure of the material) as a function of frequency provides useful information about the strength of the material. Preliminary oscillatory amplitude sweep experiments are usually performed to determine the LVE regime (where the response of material is independent of applied stress/strain). The frequency sweep tests are then performed by selecting the appropriate amplitude of oscillation within LVE regime and the desired frequency range [17, 29]. The results can either be plotted as moduli (storage and loss) vs. frequency or complex modulus and phase angle as a function of frequency. In addition to small amplitude oscillatory experiments, large amplitude oscillatory tests have also been reported in literature to analyze the nonlinear response of mud in terms of stress waveform and Lissajous pattern [41].

4. Rheological modeling of mud

4.1 Flow curve

In literature, the rheological behavior (i.e., flow curve) of mud has been fitted with numerous empirical or semi-empirical models including Bingham [52], Herschel-Bulkley [53], Worrall-Tuliani [54], and Toorman model [48], given as follows:

Bingham model:

$$\tau = \tau_B + K\dot{\gamma} \tag{1}$$

Herschel-Bulkley model:

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{2}$$

Worrall-Tuliani model:

$$\tau = \tau_0 + \mu_\infty\dot{\gamma} + \frac{(\mu_0 - \mu_\infty)\dot{\gamma}}{1 + \frac{\mu_0 - \mu_\infty}{\tau_\infty - \tau_0}\dot{\gamma}} = \tau_0 + \mu_\infty\dot{\gamma} + \frac{\Delta\mu\dot{\gamma}}{1 + \beta\dot{\gamma}} \tag{3}$$

Toorman model:

$$\tau = \lambda\tau_0 + (\mu_\infty + c\lambda + \beta\tau_0\lambda_e)\dot{\gamma} \tag{4}$$

where K is the consistency index, μ_0 and μ_∞ are the viscosities at lower and higher shear rates, n is the flow behavior index, τ_0 is the yield stress and τ_∞ and τ_B are the Bingham yield stresses at high shear, λ is the structural parameter which varies between 0 and 1, λ_e is the equilibrium structural parameter and β is the ratio of breakdown and aggregation parameter. However, all these models are suited to fit the experimental data of flow curve with only single step yielding.

4.1.1 Empirical model for two-step yielding

It has been reported in literature that mud samples usually exhibit a two-step yielding phenomenon [17, 41, 51], which is associated with two yield stresses. These two yield points depict the transition between a fully structured sample (i.e., interconnected network of flocs), partially structured sample (i.e., mobile flocs) and almost fully disturbed sample (i.e., smaller flocs or particles). Therefore, the shear stress as a function of shear rate for the whole investigated range can be written as a sum of two functions, which represent the two yield regions, given as:

$$\tau = \alpha\tau_{stat} + (1 - \alpha)\tau_{fluid} \tag{5}$$

where α is a step function given by:

$$\alpha = 1 - \frac{1}{1 + \exp\left(-k(\dot{\gamma} - \dot{\gamma}_0)\right)} \tag{6}$$

where $\dot{\gamma}_0$ represents the shear rate at which the transition between the two regions occurs and its sharpness varies as a function of parameter k. The stress function for the first yield region can be written as follows:

$$\tau_{stat} = \frac{\tau_s}{1 + \dot{\gamma}_s/\dot{\gamma}} \tag{7}$$

The shear stress τ_s represents the first yield point typically known as static yield point and the shear rate $\dot{\gamma}_s$ can be used to control the curvature of this stress function. The stress function for the second yield region can be given by:

$$\tau_{fluid} = \tau_s + \frac{\tau_f}{1 + \left(\left(\dot{\gamma}_f - \dot{\gamma}_0\right)/(\dot{\gamma} - \dot{\gamma}_0)\right)^d} + \mu_\infty(\dot{\gamma} - \dot{\gamma}_0) \tag{8}$$

The shear stress τ_f represents the second yield point typically known as fluidic yield point and the parameter d can be used to tune the sharpness of this function.

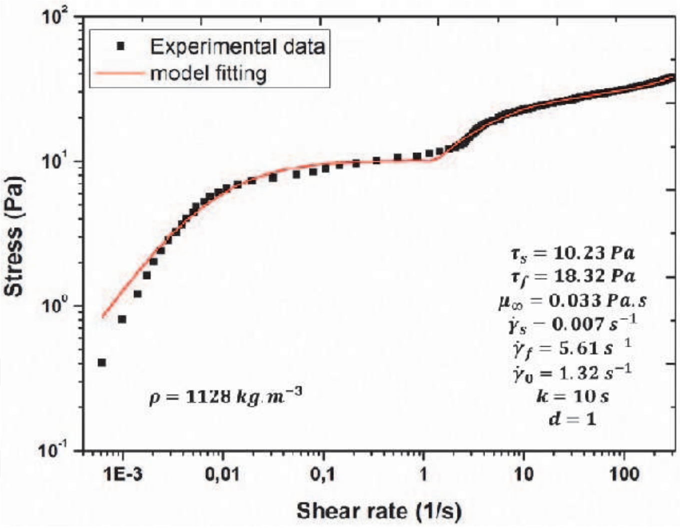

Figure 6.
Shear stress as a function of shear rate for mud sample from port of Hamburg obtained by performing stress ramp-up test using Couette geometry. The solid line represents the two-step yielding model fitting Eq. (5). Reprinted from Ref. [46].

Figure 6 shows the fitting of experimental data obtained for the mud sample from Port of Hamburg using Eq. (5) along with the values of fitting parameters.

4.2 Structural recovery

The experimental data of structural recovery tests (i.e., storage modulus as a function of time) can be easily fitted with the stretched exponential function [51] given as follows:

$$\frac{G'}{G'_0} = \frac{G'_i}{G'_0} + \left(\left(\frac{G'_\infty - G'_i}{G'_0}\right)\left(1 - \exp\left[-\left(\frac{t}{t_r}\right)^d\right]\right)\right) \tag{9}$$

where G' represents the storage modulus recorded as a function of time after pre-shear step, G'_0 denotes the initial storage modulus value before pre-shear step, G'_i is the storage modulus value recorded immediately after pre-shear step, and d is the stretching exponent. The two remaining parameters, i.e., G'_∞ and t_r represent the equilibrium storage modulus of the system and the characteristic time of recovery (the time required to attain 63% of equilibrium storage modulus), respectively. These two parameters provide the strength of recovered structure and the time required to regain its strength, which is useful information for ports and waterways applications, where the mud is disturbed by natural or human activities in the ports.

5. Factors affecting rheological properties of mud

5.1 Density

Density (i.e., solid content and water content) is an important characteristic of mud which can significantly affect their rheological behavior, such as yield stress, thixotropy and moduli. In natural environment, the density gradient in mud is usually created by wave motion or human activities along with settling of particles. In literature, several researchers have reported the rheological characteristics of mud as a function of solid content or density [9, 17, 23, 26, 27, 29, 55]. For instance, the mud obtained from Lianyungang, China showed an exponential increase in yield stress as a function of volume concentration of particles [29]. Likewise, the similar exponential relation between yield stress and solid content or water content of mud has also been reported by other researchers for samples obtained from different ports [17, 26, 27, 55].

However, this 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 7a**. It can be seen that the dependence of yield stress on mud density is significantly different for the samples collected at different locations. In order to further quantify this difference, both the fitting parameter 'a' for the power law relation given in the caption of **Figure 7a** and the total organic carbon (TOC) are plotted as function of different locations (**Figure 7b**). There is clearly a correlation between the TOC content and the fitting parameter 'a'. This behavior suggests that the yield stress of mud is strongly dependent both on TOC and mud density, as already reported in literature [15, 16].

Several researchers have reported the rheological characteristics of mud as a function of density either by collecting natural mud layers with varying density [17] or by diluting dense mud samples [9, 23]. However, it has been observed that the natural and diluted mud layers display significantly different rheological properties [24] (see **Figure 8**), which may again be linked to the composition of each mud layer, procedure of dilution, etc.

Apart from yield stress, other rheological properties including moduli, thixotropy, structural recovery, etc. are also strongly dependent on the density of mud samples [24, 51]. For instance, the structural recovery, observed by using above mentioned protocol (Section 3.2), for mud samples collected from different locations and different depths is shown in **Figure 9a** and **b**, respectively. From the figure, it is found that the structural recovery (i.e., moduli values) of mud is highly dependent on the mud layer, and position in the harbor [51]. Hence, density of mud is a critical parameter particularly for describing their rheological characteristics, however, for defining nautical bottom in ports only density is not enough and other parameters also need attention from the researchers.

5.2 Organic matter content (TOC) and its degradation

The presence of organic matter in mud usually hinders the settling of particles and can help to form fluid mud layers, in addition to the natural wave motion or

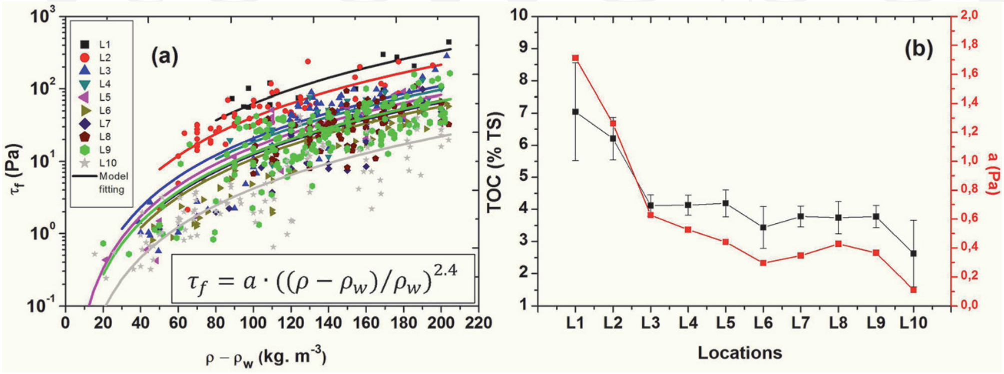

Figure 7.
(a) Fluidic yield stress (τ_f) as a function of excess density ($\rho - \rho_w$) for mud samples from different locations of port of Hamburg. The solid lines represent the power law fitting with one fitting parameter 'a'. ρ_w represents the density of water. L1 to L10 represent the locations from river towards sea side in the Port of Hamburg. (b) Fitting parameter 'a' and TOC as a function of different locations of port of Hamburg. Reprinted from Ref. [46].

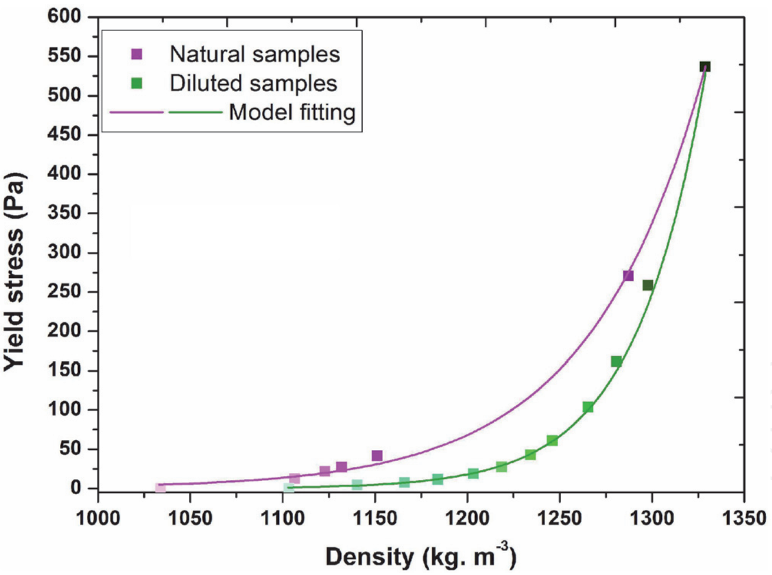

Figure 8.
Fluidic yield stress values vs. bulk density for natural and diluted mud layers from Port of Hamburg. Solid lines represent the power law fitting. Reprinted from Ref. [24].

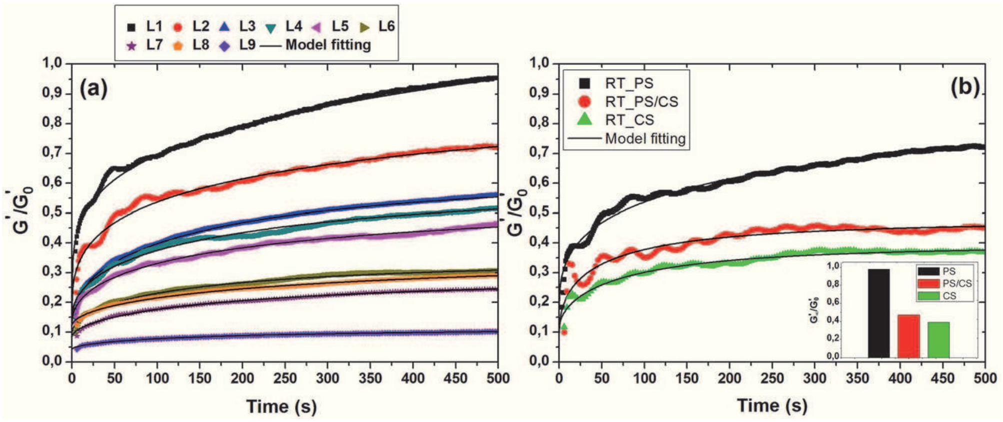

Figure 9.
(a) Normalized storage modulus (G'/G'_0) as a function of time for pre-consolidated (PS) sediment samples obtained from different locations of port of Hamburg and pre-sheared at 100 s^{-1} using Couette geometry, L1 to L10 represent the locations from river towards sea side in the port of Hamburg with similar densities. (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. Reprinted from Ref. [51].

human activities which are also responsible for the existence of these 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) [56]. 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 [32].

The existence of organic matter in mud is also known to significantly influence the rheological and cohesive properties of mud [10, 14, 15]. For instance, the rheological characteristics of mud have been investigated in literature by varying organic matter content and keeping density constant [16]. The results showed an increase in yield stresses and moduli of mud with increasing organic matter content, for a similar density value (see **Figure 10a**). However, further research is required to investigate the effect of type of organic matter/biopolymer at different pH or ionic concentrations on the rheological behavior of mud.

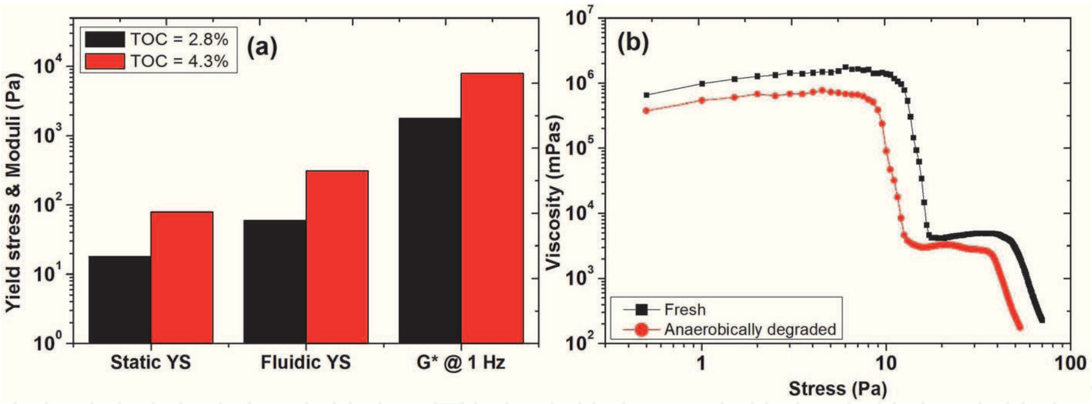

Figure 10.
(a) Yield stress values and complex modulus at 1 Hz for mud samples having similar density (1210 kg. M^{-3}*) and different organic matter content obtained from port of Hamburg, adapted from ref. [16] (b) apparent viscosity as a function of shear stress for fresh and anaerobically degraded 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 [32]. For a detailed information about the aerobic and anaerobic degradation of mud, see ref. [32]. 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 10b**. It can be seen that the values of the two yield stresses (static and fluidic) for degraded sample are significantly lower than the fresh ones. 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.

6. Discussion

The yield stress dependency on mud density is observed to vary for the samples collected from different parts of the world. As an example, fluidic yield stress values are plotted as a function of density for the samples collected from different ports (see **Figure 11**). 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 and content of TOC, ionic strength, etc. This behavior highlights the needs for a systematic investigation of the rheological properties of mud, as function of relevant parameters, for different ports.

Furthermore, the values of the rheological characteristics including yield stress and storage modulus of mud samples collected from different parts of the world are compared in **Table 3**. It can be seen that the mud from the Port of Santos [27], the Hangzhou Bay, China [23], the Port of Rotterdam [9], and the Port of Hamburg [16] display similar values of rheological properties for similar densities. However, the mud samples obtained from Mouth of Yangtze River, Shoal of Hangzhou Bay, and Yangcheng Lake, China [44] possess higher values of rheological parameters, which may be attributed to the their higher densities. Moreover, the mud from Eckernförde Bay, Germany show considerably lower yield stress values for the

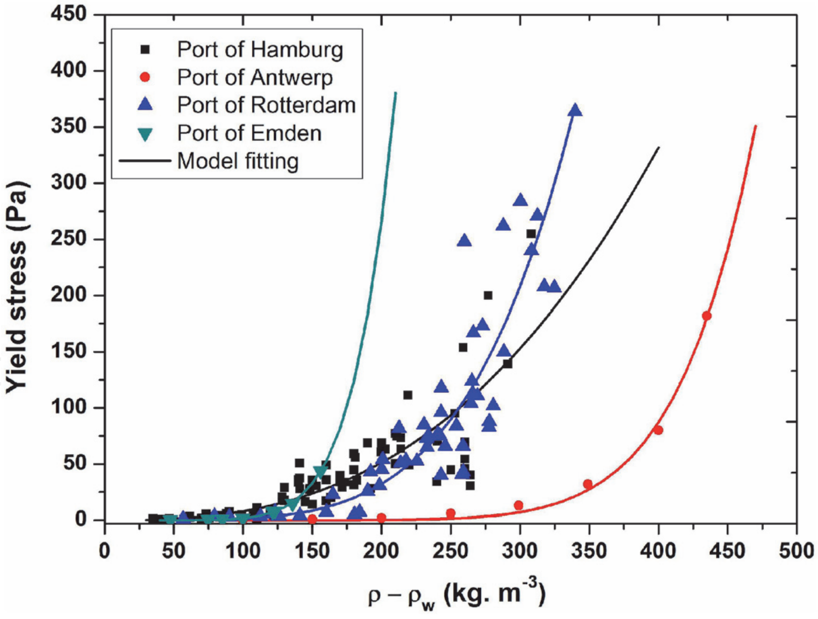

Figure 11.
Fluidic yield stress as a function of excess density $(\rho - \rho_w)$ *for mud samples collected from different ports.*

Location	Bulk Density (kg/m^3)	Fluidic Yield Stress (Pa)	Storage Modulus @ 1 Hz (Pa)	Ref.
Port of Rotterdam, the Netherlands	1168	7	45	[9]
Eckernförde Bay, Germany	1038–1280	1.07–20.50	—	[31]
Hangzhou Bay, China	1145–1634	0.55–40	0.02–15	[23]
Mouth of Yangtze River, China	1650–1700	910–2810	—	[44]
Shoal of Hangzhou Bay, China	1705–1741	772–2140	—	[44]
Yangcheng Lake, China	1651–1691	2070–3960	—	[44]
Lianyungang Port, China	1098–1305	0.098–28.029	2–1050	[29]
Port of Santos, Brazil	1085–1206	5–334	—	[27]
Port of Rio Grande, Brazil	1132–1308	5–350	—	[27]
Port of Itajaí, Brazil	1138–1360	5–299	—	[27]
Amazon South Channel	1293–1512	5–379		[27]
Port of Hamburg, Germany	1087–1210	2.44–312	0.47–7915	[16]

Table 3.
Comparison of rheological properties (i.e., yield stress and storage modulus) of mud samples obtained from different sources.

comparable densities, which may be linked to the organic matter content or measuring protocol.

As already mentioned that the yield stress can be used as a criterion to define navigable fluid mud layers, Port of Emden, Germany is reported to use the yield stress of 100 Pa as a criterion for nautical bottom [15]. However, this critical value of yield stress for defining nautical bottom is significantly dependent on the spatial variation of the sediment characteristics (i.e., sand content, organic matter content, etc.). For instance, the rheological properties of mud samples from Port of

Hamburg, Germany are significantly different for different locations within the port, due to the different organic matter content [46]. Therefore, using a single value of yield stress as a criterion for defining nautical bottom for the whole port can be quite tricky and instead, different boundaries of yield stress as a function of density can be used for different locations, in order to define the nautical bottom.

7. Conclusions

In this chapter the rheological behavior of mud as found in harbors, is discussed. Different mud layers, formed as a result of either natural or human activities, were defined. These mud layers exhibit a complex rheological fingerprint, by displaying a combination of thixotropy, two-step yielding behavior and viscoelasticity, which is conventionally associated to the existence of clay flocs (aggregated clay particles with organic matter). The analysis of the rheological properties of the top layer (fluid mud layer) is crucial for navigational purposes, optimizing dredging operations and the proper maintenance of dredged navigational channels.

In order to study the rheology of mud in laboratory, it was found that core sampling is the best sampling technique as it allows to collect mud samples without much disturbance. In contrast to what some authors do, it is not recommended to dilute a specific sample to predict its rheological behavior as function of density. It is shown that the rheological properties of natural mud layers of different densities found on top of each other at a specific location in the harbor do not match the properties of samples obtained from diluting the densest (deepest) mud layer sample. The reason lays in the differences in mud composition and structure at different depths.

The determination of yield stress of mud is highly dependent on the selected rheological geometry and experimental method. A detailed analysis shows that the Couette geometry along with stress ramp-up test is the most suitable combination to analyze the yield stress of mud for ports and waterways applications. The optimization of this stress ramp-up test enables to reduce the experimental time for different mud layers ($\sim$ 10–200 s). Several empirical or semi-empirical models are available in literature to fit the experimental data of mud displaying a single-step yielding. However, the mud samples are observed to exhibit a two-step yielding and, therefore, the behavior of shear stress as a function of shear rate (i.e., flow curve) can be represented as a sum of two functions, which capture the two yield regions. The model captures the two-step yielding phenomenon in mud samples quite well, within the density range of 1050–1200 kg. m^{-3}.

Several factors are known to influence the rheological characteristics of mud such as density and organic matter content. An exponential relation between yield stress and density (i.e., solid content) is usually observed in literature for mud from different sources. However, this correlation between yield stress and density is highly dependent on the mud composition. Apart from yield stress, other rheological properties including moduli, thixotropy, structural recovery, etc. are also strongly dependent on the density and composition of mud samples. For instance, the fluidic yield stress of mud from Port of Hamburg, Germany is observed to increase from 79 Pa to 312 Pa by increasing the organic matter content from 2.8% to 4.3%. The degradation of organic matter in mud, which can occur over time for different layers is found to significantly influence the rheological and cohesive properties of mud. Further research is required to investigate the effect of type of organic matter at different pH or ion type and concentrations on the rheological fingerprint of mud.

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Conflict of interest

The authors declare no conflict of interest.

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