RHEOLOGICAL PROPERTIES OF MARINE SEDIMENTS FROM THE PORT OF KOPER

Jasna Smolar *(corresponding author)*
University of Ljubljana,
Faculty of Civil and Geodetic Engineering
Jamova 2, Ljubljana, Slovenia
E-mail: jasna.smolar@fgg.uni-lj.si

Matej Maček
University of Ljubljana,
Faculty of Civil and Geodetic Engineering
Jamova 2, Ljubljana, Slovenia
E-mail: matej.macek@fgg.uni-lj.si

Ana Petkovšek
University of Ljubljana,
Faculty of Civil and Geodetic Engineering
Jamova 2, Ljubljana, Slovenia
E-mail: ana.petkovsek@fgg.uni-lj.si

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Abstract

Subaqueous, fine-grained, cohesive sediments are continuously fluidized by waves and other disturbances that cause their movement, which can be described with numerical models incorporating rheological parameters. The rheological behaviour depends on the soil (solid) type, the volume concentration, the salinity and the testing methods.

In this study, rheological investigations of marine sediments from the Port of Koper were carried out by using two coaxial cylinder rheometers (DV3T HB, Brookfield and ConTec Viscometer 5). The influence of the specimen volume, the size of the gap and the type of measuring spindles were analysed and compared.

The measured data were evaluated using the Bingham model. For each data set, the boundary between the sheared ("fluid") and the un-sheared ("solid") material was calculated and then the calculated boundary was used instead of the outer radius of the cylinder for the evaluation of the rheological parameters, where necessary.

A good comparison of the results was found when using this approach. The results are also in agreement with the literature data. The ConTec Viscometer 5, primarily designed for mortars and concrete, was shown to be also suitable for the investigation of sediments.

1 INTRODUCTION

Subaqueous sediments are continuously fluidized by waves and other disturbances that cause their transport over short or long distances. Sediment movements can also be accompanied by the migration of pollutants. To characterize the flow behaviours of sediments, numerical models of flow mechanics are used and the two rheological parameters, yield stress and viscosity, are required [1 - 6].

Recently, extensive investigations have been carried out in order to provide the rheological parameters of different types of subaqueous and subaerial mud and debris flows [3, 5, 7-18, among others]. The results show that the rheological parameters strongly depend on the soil (solid) type, the volume concentration, the salinity of the pore water, and the type and geometry of the rheometer [2, 6, 19].

In this study the rheological parameters of remolded marine sediments from the Port of Koper, Adriatic Sea, were investigated for the first time. The port is facing the permanent accumulation of fine-grained, cohesive sediments inside the existing waterways, while the wider area of the Gulf of Trieste is facing the migration of pollutants [20-25, among others]. The prediction of the runout distances and the impacts due to the sediment transport are an important part of the risk analysis and mitigation measures in the port area.

The second goal of the study was to investigate how the use of different types of rheometers, specimen sizes and the measuring spindles can influence the results, reliability and repeatability of the measured rheological parameters.

2 RHEOLOGICAL BEHAVIOUR OF FINE GRAINED, COHESIVE SEDIMENTS

Soft cohesive sediments and slurries display non-Newtonian flow behaviour, which is both strain-rate and time dependent. This rheological behaviour is generally described by the relationship between the shear stress (τ) and the shear rate ($\dot{\gamma}$). The Bingham model is one of the simplest and most popular models for a description of pseudoplastic materials (Equation 1, Fig. 1 (a)) [5, 7, 9]. In this model the shear stress has two components, i.e., shear strength or yield stress (τ_y), and an increase of the shear stress due to shear rate and plastic viscosity (η_p).

$$\tau = \tau_y + \eta_p \cdot \dot{\gamma} \qquad (1)$$

Various types of rheometers were developed for investigating the rheological parameters of different materials (e.g., rotational rheometers/viscometers - coaxial cylinder, plate-plate, cone-plate; capillary viscometers and falling-ball viscometers) [26]. Rotational rheometers/viscometers with coaxial cylinders have been widely used for investigating the rheological parameters of sediments for decades [3, 4, 7-10, 27].

In coaxial cylinder rheometers, when high-yield-stress materials are tested, the material between the inner and the outer cylinder may not be entirely sheared. The boundary between the sheared "fluid" and un-sheared "solid" is called the plug radius (R_p) [28] (Fig. 1 (b)).

The plug radius is formed when the shear stress is equal to the yield stress and can be calculated as follows [28, 29]:

$$R_p = \sqrt{\frac{T}{\tau_y \cdot 2 \cdot \pi \cdot h}} \qquad (2)$$

where T is the torque (Nm), measured in the coaxial cylinder rheometer, and h is the height of the inner cylinder submerged in the material.

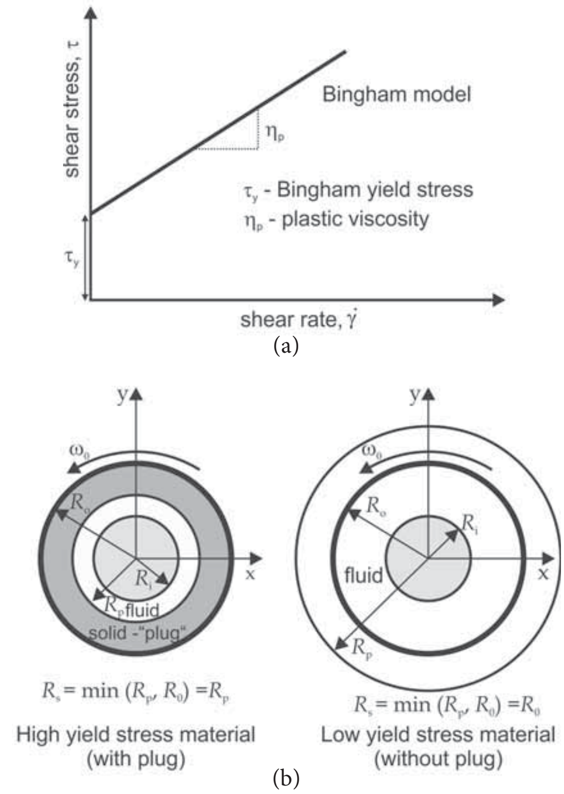

Figure 1. Bingham model (a), and top view of coaxial cylinder with sample (b) [28].

From the measured sets of rotational velocity (velocity of revolution) (N) and the corresponding torque (T), the Bingham yield stress (τ_y) and the plastic viscosity (η_p) can be calculated using Equation 3 and the least-squares method.

$$T = \frac{4 \cdot \pi \cdot h \cdot ln\left(\frac{R_s}{R_i}\right)}{\left(\frac{1}{R_i^2} - \frac{1}{R_s^2}\right)} \cdot \tau_y + \frac{8 \cdot \pi^2 \cdot h}{\left(\frac{1}{R_i^2} - \frac{1}{R_s^2}\right)} \cdot \eta_p \cdot N \qquad (3)$$

where $R_s = \min(R_p, R_o)$ (Fig. 1(b)).

Equation 3 was obtained by integrating the shear rates between the inner and outer cylinders in the coaxial cylinder rheometer and using the Bingham model [28].

For a graphical presentation of the flow curves, the shear rate is calculated using Equation 4.

$$\dot{\gamma} = \frac{T}{2 \cdot \pi \cdot R_i^2 \cdot h \cdot \eta_p} - \frac{\frac{T}{4 \cdot \pi \cdot h} \cdot \left(\frac{1}{R_i^2} - \frac{1}{R_s^2}\right)}{\eta_p \cdot ln\left(\frac{R_s}{R_i}\right)} + \frac{\omega_0}{ln\left(\frac{R_s}{R_i}\right)} \qquad (4)$$

where $\omega_0 = (2\pi/60)\, N$; N=RPM.

3 MATERIALS AND METHODS

3.1 Materials

The material used in this study is a fine-grained marine sediment from the Port of Koper. Table 1 presents the index properties and Fig. 2 shows a representative area of the grain size distribution. The investigated sediments consist mainly of illite, muscovite and chlorite [30].

The index tests show that salinity has no impact on the liquid limit and the plasticity index of the sediment (Table 1). The results are in good agreement with the literature data [31], [32] and others.

Table 1. Index properties of marine sediment.

Index properties	Material			
	marine sediment		marine clay*	
Natural water content, w_0 [33]	/	~80%	/	/
Salinity, s (g/L)	0	30	0	50
Liquid limit, w_L (%) [34]	64-67	69	72	74
Plasticity index, I_P (%) [34]	44-46	46	34	34
Water adsorption, w_A [35]	76-84	/	/	/

*Literature data [31].

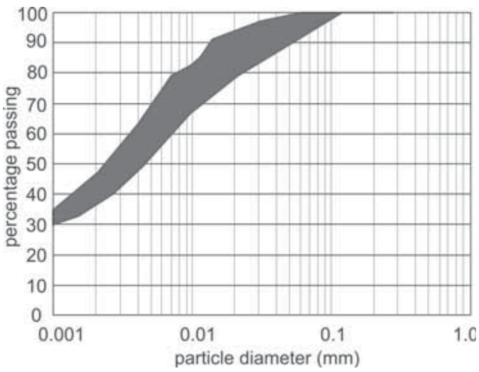

Figure 2. Representative area of grain size distribution.

3.2 Testing procedures

Two types of shear-rate-controlled coaxial cylinder rheometers were used: the DV3T HB (Brookfield) and the ConTec Viscometer 5. The main differences between these rheometers are the specimen volume and the gap size. All the investigations were carried out at room temperature (22–24 °C), on washed specimens without any salt content (s = 0 g/L).

3.2.1 DV3T HB Rheometer

Tests in the DV3T HB rheometer were conducted by using different combinations of smooth spindles (*S*), vanes (*V*) and chambers (Table 2, Fig. 3). In the evaluation of the results, the effective length of the spindles was used [36].

Table 2. Combinations of smooth spindles, vanes and chambers.

Combination	Glass beaker (GB)	Small sample adapter (SA)
Smooth spindle (*S*)	V_s ~ 800 ml *Ro* ~ 40 mm gap ~ 31-34 mm[1]	V_s ~ 7-14 ml *Ro* ~ 9.525 mm gap ~ 1.14-3.645 mm[1]
Vane (*V*)	V_s ~ 800 ml *Ro* ~ 40 mm gap ~ 23-34 mm[1]	/

[1] Gap size depends on the radius of the spindle or vane.
V_s – specimen volume, *Ro* – radius of outer cylinder, gap – distance between inner and outer cylinder

(a)

(b)

(c)

Figure 3. DV3T HB rheometer (a), small sample adapter with smooth spindles (b) and vanes (c).

Regardless of the combination of chamber and spindle, the "down curves" were measured. It consisted of measured values during decreasing the rotational velocity from 250 to 0.02 rounds/minute (RPM). Each step (at the desired rotational velocity) lasted until the spindle or vane had rotated for at least one revolution (360°) or at least 1 minute at velocities higher than 1 RPM. The resulting torque was calculated for each step as the average of the measured values after reaching equilibrium. During the investigation the outer cylinder was fixed, while the spindle or vane were rotating.

3.2.2 ConTec Viscometer 5

The ConTec Viscometer 5 (CTV 5) was primarily designed for the rheological testing of fresh mortars and concrete. It has an inner radius of 100 mm and an outer radius of 145 mm (with a 45 mm gap), while the height is 100 mm (Fig. 4). It allows investigations of materials with a maximum grain size of 22 mm.

Figure 4. ConTec Viscometer 5.

A pre-shear period of around 30 s is applied at the maximum rotational velocity to start the flow. During measurements the rotational velocity decreased in steps from 100 RPM to 6 RPM. The resulting torque was calculated from the 10 lowest measured values in 1 minute after 15 s of equilibration time. During the investigation the inner cylinder was fixed, while the outer one was rotating.

4 EXPERIMENTAL RESULTS

4.1 Results of tests

The physical properties of specimens are presented in Table 3.

The data, measured using different coaxial cylinder rheometers, were analyzed by using Equations 3 and 4, taking into account the radius R_s (Fig. 1). The comparison of the flow curves, determined by using two different rheometers and different vanes and spindles, are presented in Fig. 6.

Specimen S1 represents the densest specimen. During the test, a stable hollow was formed around the smooth spindle (Fig. 5).

The yield stress was measured separately with a laboratory vane at 0.25 RPM, on more than 140 specimens at a different liquidity index. The results are presented in Fig. 7 and compared with the literature data.

Table 3. Physical properties of specimens.

Specimen	water content, w (%)	liquidity index, I_L	volume concentration, C_v (%)
S1	79.5	1.34	32.2
S2	92.3	1.62	29.0
S3	103	1.86	26.7
S4	113	2.06	25.1
S5	130	2.44	22.4
S6	142	2.70	21.0

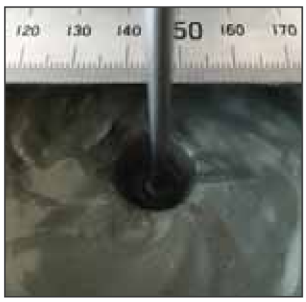

Figure 5. Stable hollow around the spindle during the investigation of S1.

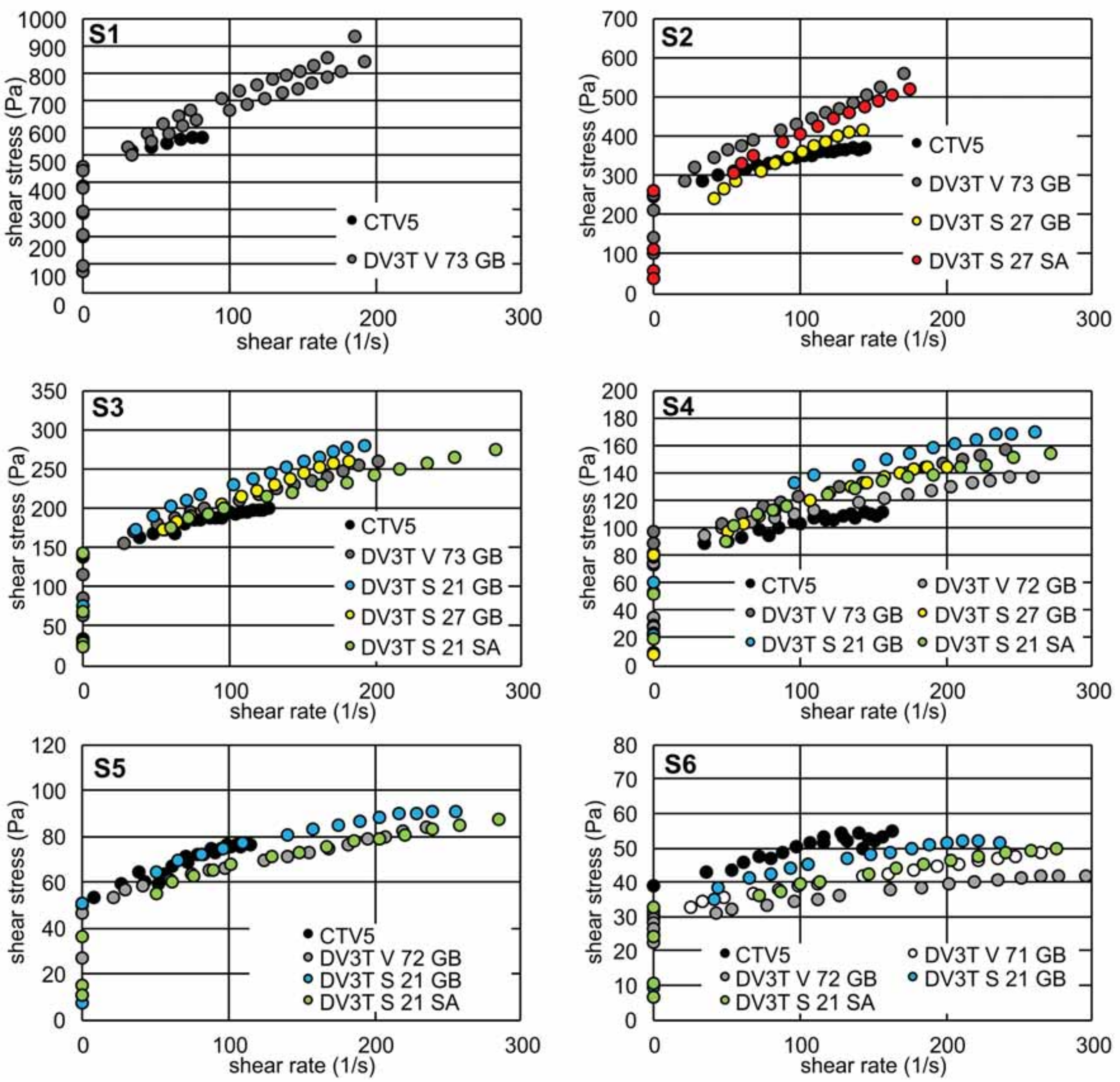

Figure 6. Flow curves of marine sediment for different water contents. Legend: CTV5 – ConTec Viscometer 5, DV3T – Rheometer DV3T HB, V – vane, S – spindle, 72 or 21 – number of vane or spindle, GB – glass beaker, SA – small sample adapter.

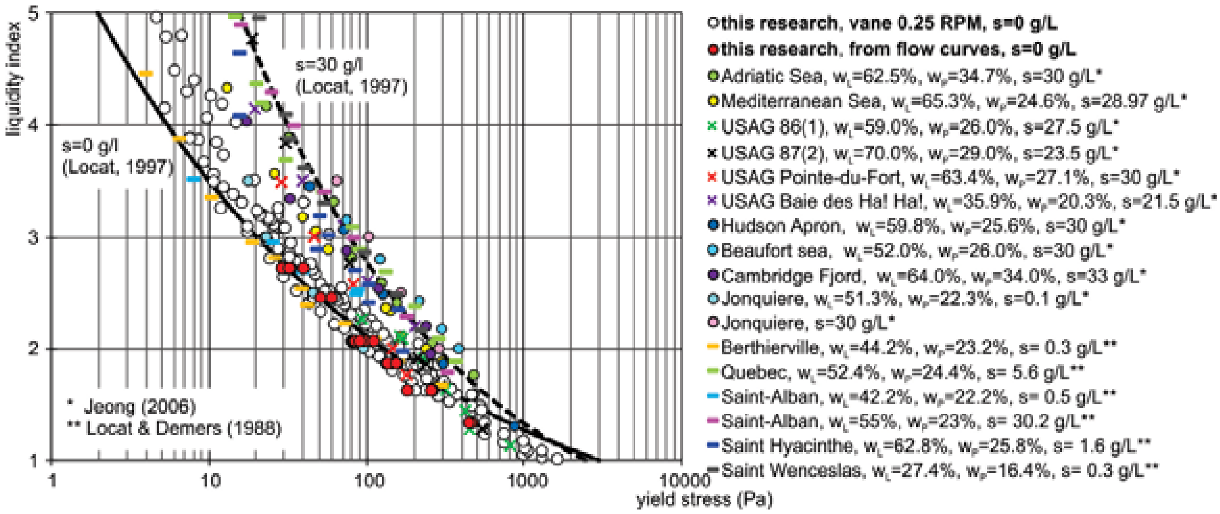

Figure 7. Yield stress and liquidity index of the investigated marine sediments in comparison with the literature data [9, 27, 37].

Table 4. Bingham rheological parameters of marine sediments, determined with different rheometers and spindles.

Specimen	S1		S2		S3		S4		S5		S6	
Parameter	τ_y	η_p	τ_y	η_p	τ_y	η_p	τ_y	η_p	τ_y	η_p	τ_y	η_p
CTV 5	476	1151	270	731	143	504	83.4	186	51.9	231	40.6	86
DV3T V71 GB	/	/	/	/	/	/	/	/	/	/	32.2	63
DV3T V72 GB	/	/	/	/	/	/	86.6-91.3	188-219	52.0	137	29.7	45
DV3T V73 GB	456-474	1998-2350	269	1637	149	561	97.1	247	/	/	/	/
DV3T 21S GB	/	/	/	/	159	660	113	229	61.2	128	34.1	85
DV3T 27S GB	/	/	186	1686	140	679	84.9	320	/	/	/	/
DV3T 21S SA	/	/	/	/	158	422	86.3	272	52.3	129	33.1	62
DV3T 27S SA	/	/	260	1457	/	/	/	/	/	/	/	/

τ_y (Pa), η_p (mPa·s)

4.2 Analysis of the measured rheological parameters

An analysis of the results shows that the rheometer type and the geometry of the spindles do not influence the results (Table 4). The observed scattering of the results seems to be more influenced by the experiment itself than by the type of rheometer.

4.3 Comparison of the measured parameters with the literature data

The results of the investigated marine sediments were analyzed in comparison with the literature data [9, 11-13, 15-18, 27] and by using the empirical relationships (Equations 5 to 7) for the calculation of the yield stress and plastic viscosity from the index test results [37].

$$\eta_p = \left(\frac{9.27}{I_L}\right)^{3.3} \tag{5}$$

$$\tau_y = \left(\frac{5.81}{I_L}\right)^{4.55} \tag{6}$$

$$\tau_y = \left(\frac{12.05}{I_L}\right)^{3.13} \tag{7}$$

where I_L is the liquidity index.

Equation 5 is valid for natural soft clays in the range of I_L between 1 and 5, where η_p represents only about 1/1000th of the total shearing resistance. Equation 6 is valid for very low salinity (s) sensitive clays and Equation 7 for clays with a salt content of about 30 g/l.

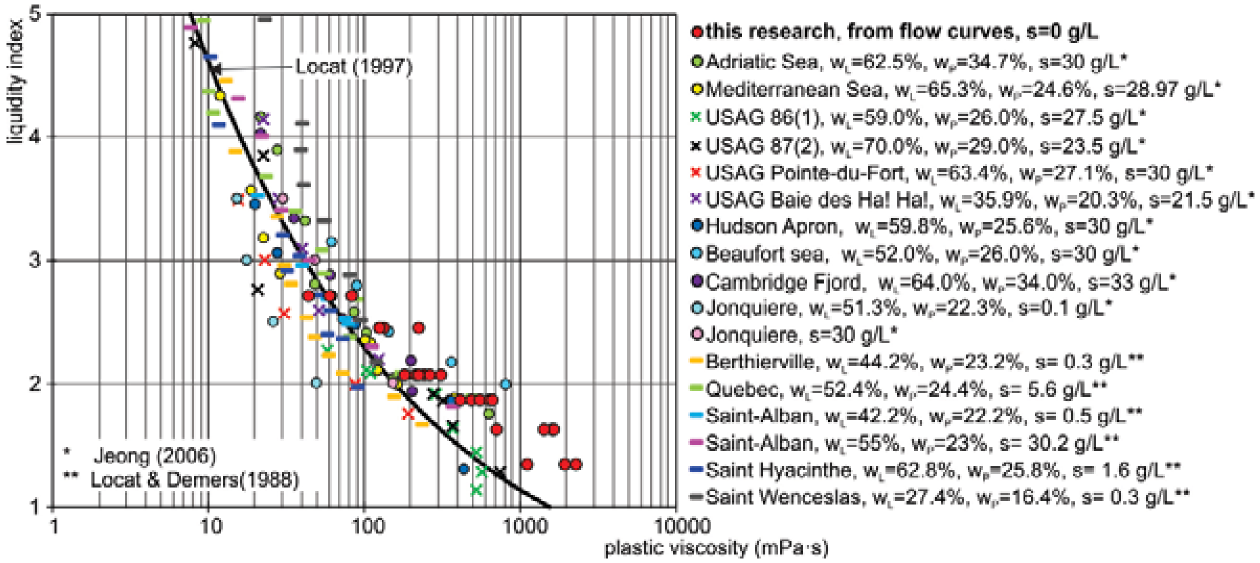

Figure 8. Plastic viscosity and liquidity index of the investigated marine sediments in comparison with the literature data [9, 27, 37].

Fig. 7 shows the yield stress and Fig. 8 the plastic viscosity, measured on sediments from the Port of Koper, in comparison with literature data. The index parameters (w_L,w_P) of the literature data are summarized in the legends of the figures. The black lines in Figs. 7 and 8 show the parameters calculated using empirical correlations (Equations 5 to 7). Both the shear stress and the plastic viscosity of the marine sediments from the Port of Koper are in relatively good agreement with the literature data. The yield stress is close to the values given by Equation 6, independently of the method. The plastic viscosity at the lower liquidity index is up to 4 times higher than that calculated from Equation 5. The same range of scatter was also found in the literature data.

One of the important factors that affect the rheological parameters is the soil texture. Thus, it is interesting to analyze the relationship between the index properties of the sediments and their rheological parameters (Fig. 9). The results of the investigated marine sediments fall close to clay-rich materials, which is in good agreement with the index properties given in Table 1.

5 CONCLUSIONS

The Bingham rheological parameters of cohesive marine sediments from the Port of Koper were, for the first time, determined by using a small DV3T HB rheometer and a large ConTec Viscometer 5. The measured data were analysed and compared to the literature data. The main conclusions are as follows:

(1) the investigated marine sediments behave as a Bingham-type viscoplastic fluid

(2) the rheological parameters (τ_y , η_p), calculated by using R_s = min(R_p ,Ro), measured with both rheometers, are in the same range and are independent of the size of the gap

(3) the ConTec Viscometer 5 was found to be suitable for rheological investigations of the cohesive sediments

(4) the rheological parameters of the marine sediments from the Port of Koper are in good agreement with literature data and also with empirical correlations.

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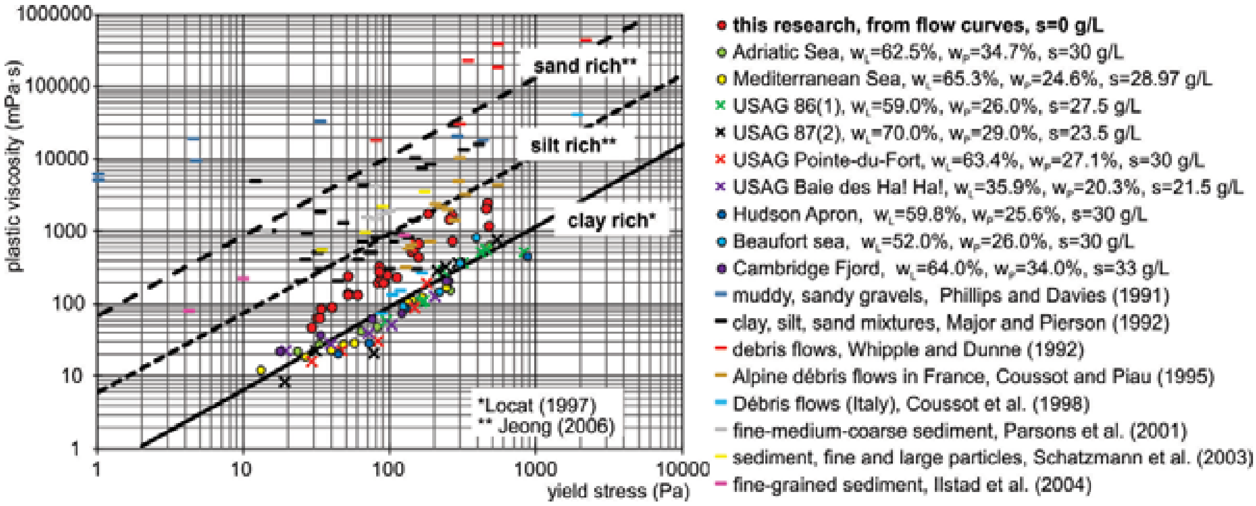

Figure 9. Yield stress versus plastic viscosity for a variety of soil types [9, 11–13, 15–18, 27].

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