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Conditioning procedures to enhance the reproducibility of mud settling and consolidation experiments

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A R T I C L E I N F O

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A B S T R A C T

The means by which mud is conditioned for use in laboratory experiments affects the behaviour of the mud during the experiments, and hence the results and reproducibility. This study discusses the impact of different mud conditioning techniques and procedures using multiple series of short-term consolidation tests. The mud used originates from the Zeebrugge docks of the Port of Antwerp-Bruges, Belgium. For all experiments the initial density of the mud was around 1.08 g· cm^{-3}, which is below its gel density. This has the advantage that the comparison can be limited to the behaviour during the typical initial settling phases, allowing experiments to be restricted in time to seven days. Each series of experiments is repeated multiple times using two separate batches of mud. The objective is to quantify the repeatability across these different series of experiments, and to identify the ideal conditioning procedure for optimal reproducibility for future laboratory experiments using mud. Distinct differences in settling curves are observed which confirm the intended influence of each mixing technique. A conditioning procedure based on a combination of axial and radial mixing yields the most control over settling behaviour during the initial stages of the sedimentation process and therefore results in the best repeatability of settling behaviour. It is recommended that such a mud conditioning procedure is further used for experiments with mud to allow for a better uniformity in research where the behaviour of mud is critical.

1. Introduction

1.1. Nautical research using mud in physical experiments

In 1997 the concept of the "nautical bottom" was introduced by PIANC (The World Association for Waterborne Transport Infrastructure) as "the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and maneuverability" (Vantorre, 1997). In case of sand or rock bottoms, the depth of the nautical bottom is directly determined by the highest sand dune or rock outcrop. When the bottom of navigation areas consists of mud, there is however no clear physical limit which determines the applicable nautical bottom. Nonetheless, the presence of such muddy layers can influence the maneuverability and controllability of ships, even when the keel of the ship does not penetrate these layers (Delefortrie et al., 2007; Delefortrie and Vantorre, 2009). Due to the complex interactions between ship, mud and water layers, the use of Computational Fluid Dynamics (CFD) models is recently preferred by nautical researchers to facilitate the research on the influence of a mud layer on a ships' maneuvering behaviour (Vanlede et al., 2014; Delefortrie and Vantorre, 2016). Development of such CFD models requires validation data, preferably generated by physical laboratory tests using natural mud (Toorman et al., 2015; Lovato et al., 2022; Sotelo et al., 2022). Typically these experiments consist of a body which is towed through a mud layer. During towing, the forces and pressures acting on the body are monitored. In preparation, the mud is homogenised (conditioned) prior to each experiment and a sample of the mud is taken to determine the rheological properties of the mud. This way, the forces and pressures acting on the body can be related to the mud properties. Due to practical limitations the time between the conditioning of the mud and the start of the experiments may be several hours.

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1.2. Settling and consolidation experiments of mud

In the fields of geotechnical and marine engineering, the term "mud" is used as a general term for cohesive coastal and estuarine sediments. Mud is a complex mixture of water, various clay minerals, organic matter and small amounts of sand and silt (Berlamont et al., 1993). The grain size of the mud considered in this study, ranges from 0.3 μm to 120 μm with a median grain size (d50) of 6.5 μm, indicating a majority of clay minerals and organic material. For decades, the behaviour of mud has been the subject of many research projects in support of various hydraulic, chemical and mechanical engineering challenges (Toorman, 1997). Many of these studies focused on the sedimentation physics by means of settling and consolidation experiments. Conceptually, these experiments are all similar. A preconditioned batch of mud is introduced into a transparent vertical tube and left at rest for a period of time to allow sedimentation and consolidation. To fully comprehend the physics during these sedimentation and consolidation processes, the change over time of various parameters such as mud density, pore pressure and the level of the water–mud interface is monitored (Berlamont et al., 1993). To allow for a large number of experiments in a limited period of time, only the settling of the water–mud interface was monitored during the experiments of this study. In the case of mud with a density lower than the gel density, i.e. the density from which cohesive flocs begin to come close enough to each other for chemical and electrostatic forces to form a continuous structure yielding a true yield stress (Been, 1980; Berlamont et al., 1993; Huysentruyt, 1995), settling starts almost instantly (minutes) forming a distinct interface between "clear" water and mud. This interface will settle with time. Plotting the level of this interface with time yields a settling curve. A brief description of the mechanics causing the course of the sedimentation and consolidation processes is provided in Section 1.5. Typically the characteristics of mud in the consolidation phase are of interest, because it is in this phase that mud is mostly encountered in nature. Therefore settling and consolidation experiments are usually conducted over longer periods of time up to months.

1.3. Reproducibility of the behaviour of mud

The repeatability of settling curves from settling and consolidation experiments is not always discussed objectively. In some reports it is described qualitatively (Elder, 1985; Bowden, 1988; Winterwerp et al., 1993; Merckelbach, 2000; van Rijn and Barth, 2019). Other reports discuss the possible factors that may affect reproducibility (Been and Sills, 1981; Berlamont et al., 1993; Winterwerp et al., 1993). Been and Sills (1981) intentionally conducted repetition tests, but the resulting settling curves were not published. Some published settling curves in different reports do however allow for an objective evaluation of repeatability by estimating the maximum deviation between two similar tests. Doing so for various published results, the series of experiments of Been (1980) and Merckelbach (2000) showed settling curves with a maximum deviation below 3% of the initial height. Lin (1983) and Bowden (1988) and other series of Merckelbach (2000) show results between 3% and 5%. Deviations exceeding 5% were found in Elder (1985), Dankers (2006) and Fossati et al. (2015). A recurrent observation is that deviations fully develop in the early stages of sedimentation and are maintained in the subsequent course.

For experiments as described in Section 1.1 such deviations in settling rates are unacceptable because they will result in great variation of the monitored forces and pressures. The primary effect is on buoyancy. For example, Sotelo et al. (2022) conducted his experiments in an initially 500 mm thick mud layer. In this case, a 3% deviation in settling means a variation of the mud–water interface level up to 15 mm. When towing a semi-submerged cylinder with a radius of 100 mm at a velocity of 0.5 m s^{-1} like (Sotelo et al., 2022), the difference in buoyancy due to such a variation in mud layer thickness already leads to an additional uncertainty of 3.5% on the measured drag force and 8.1% on the measured lift force. Secondly there is also the effect on the dynamics of the mud. After all, the settling rate of the cohesive fraction in the mud is one of the determining parameters for the mechanical behaviour of the mud (Berlamont et al., 1993; Teisson et al., 1993). Since this irregularity in mechanical behaviour develops in the early settlement phases, which overlap with the time window during which the experiments are conducted, this deficiency can only be remediated during the conditioning of the mud.

1.4. Conditioning of the mud

Most of the literature emphasises the importance of procedural conditioning of the mud in preparation of settling and consolidation experiments. A description of the conditioning procedure is therefore mostly included. There is however no uniformity in these procedures. In general, the objective is to homogenise the mud by agitation. However, the means by which this is done and for how long varies greatly, from minutes of stirring by hand with a wooden stick to hours of circulating pumping. A homogenised fluid indeed seems a logical condition for the quality of the experiments. Nevertheless, the repeatability of the experiments is insufficient, as discussed earlier. This could be explained by an inconsistent degree of homogenisation, or because homogenisation alone is insufficient and an additional function should be given to the conditioning.

It is the objective of this research to present a clear procedure for mud conditioning which enhances the reproducibility of mud behaviour and therefore allows for repeatable hydraulic experiments using mud. In addition, such a procedure will be beneficial for any future settling and consolidation experiments. When used uniformly, it will allow comparison of the behaviour of cohesive sediments of different origin and composition. This was already mentioned as a major shortcoming in the EC MAST-I research program report (Winterwerp et al., 1993).

1.5. Sedimentation mechanics

As mentioned in Section 1.3, the deviations between settling curves of repetitive experiments develop during the first phases of sedimentation. The conditioning of the mud should therefore mainly affect these phases. To make a targeted choice in potential useful conditioning techniques, a basic understanding of the sedimentation mechanics is therefore required.

Consider mud with an initial density below gel density, left at rest in a reservoir. In such a low energy environment, coarse and heavy particles (e.g. sand) will settle instantly, while aggregation with the formation of large flocs dominates the initial phase of flocculation for the cohesive particles. When these formed flocs are large enough that gravitation starts to prevail, these flocs too will settle down (Toorman, 1992b; Yu et al., 2022). The unhindered settling rate of the single particles and flocs are different due to difference in mass and shape. Furthermore, the upward flux of displaced water caused by the settling particles will generally increase the drag on neighbouring particles, reducing the settling velocity. This is a first reason for the occurrence of hindered settling (Toorman, 1996). Along with increasing density due to sedimentation, the probability of particle interactions, i.e. collisions, increases. These interactions add to the decrease of the settling flux, starting the hindered settling phase (Toorman, 1996). According to Toorman and Berlamont (1993), except for very watery mud (density lower than 1.03 g cm^{-3}), the settling curve of mud, during these first two phases, develops in accordance with classic sedimentation theories like (Kynch, 1952). Fig. 1 shows a typical settling curve based on Kynch's theory. During the sedimentation process, Kynch distinguishes three phases of sedimentation. During the first phase, "constant rate settling", the water–mud interface moves downward linearly with time. In this manuscript, the "constant rate settling" phase is further referred to as the "settling phase". The second phase, "hindered settling",

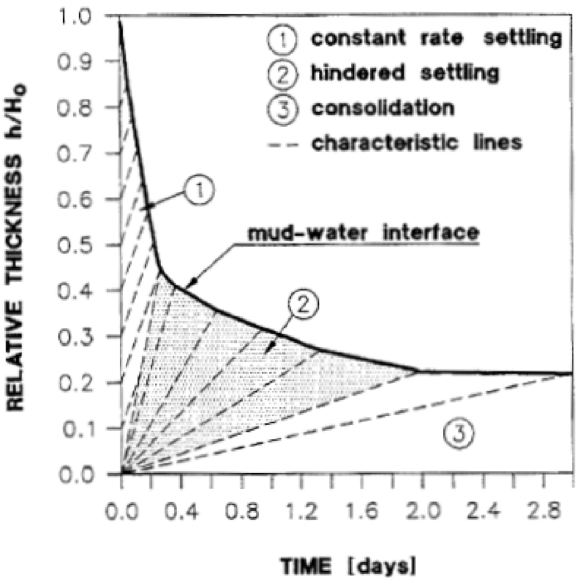

Fig. 1. Ideal settling curve based on Kynch's sedimentation theory, indicating the three phases of sedimentation and characteristic lines. The characteristic lines are iso-density lines. A change in the slope of these characteristic lines indicates a change in density. *Source:* Copied from Toorman (1992a).

starts when the settling rate starts to slow down due to increasing interaction between the particles as a result of increasing density. As stated earlier, the settling rate is a function of density. This is indicated by the characteristic lines or iso-density lines depicted in Fig. 1. The parallelism of these lines during the settling phase indicates a consistent density during this phase. While the changing slope throughout the remainder of the settling curve indicates the changing density.

With time, a density is reached that causes a second abrupt drop in settling rate, indicating the beginning of the third and final phase, the "consolidation" phase. From the consolidation phase onwards, the settling curve of mud deviates from Kynch's sedimentation theory (Toorman, 1999). The consolidation phase of mud begins when the density discontinuity between the suspension and the consolidating bed fades (Toorman, 1999). Furthermore, the consolidation phase of mud consists of two intermediate stages. First, the settling rate is determined by the permeability of the mud, since compression is mainly caused by the expulsion of pore water. Further settlement is caused by the deformation of the flocs (Toorman, 1999; Camenen and Pham van Bang, 2011). During the consolidation phase, the density will exceed the gel density after which the structure formed strongly impedes further settling. During the consolidation phase the settling rate continuously decreases and eventually tends to zero. According to Toorman (1992a), from the first part of the consolidation phase, the settling curve follows a power law function. A more detailed elaboration on the sedimentation mechanics of mud can be found in Toorman (1996, 1999) and Camenen and Pham van Bang (2011).

2. Experimental facilities

To come up with the ideal conditioning procedure, various conditioning techniques and durations are applied in preparation for multiple sedimentation and consolidation experiments. For the sake of simplicity, only the settling of the mud–water interface is recorded. The resulting settling curves are used to evaluate repeatability. Because the focus of this research is on the influence of the applied conditioning techniques, all mud samples are prepared to an equal density below the gel density. This way a possible difference in settling curve is formed more rapidly and the duration of the experiments can be limited to one week. This is different from hydraulic experiments using mud for nautical research. Here a mud density higher than the gel density is usually used. Despite the different settling mechanics for densities above the gel density, there is however no reason to believe that the effects of conditioning will be different.

2.1. Selection of conditioning techniques

Following the elaboration on sedimentation mechanics in the previous section, it is thus clear that the distribution of different particles will influence the settling behaviour. Michaels and Bolger (1962) already demonstrated the influence of floc size on the settling rate in the settling phase. Adequate mixing to influence the settling rate should therefore affect both the size of the flocs and their dispersion in the mud volume. Uncontrolled influencing is however insufficient to reproduce settling rates. To achieve this, reference states are required, which in turn should be reproducible.

2.1.1. Homogenisation by axial mixing

Homogenisation of a fluid is typically done by agitation or mixing. Proper homogenisation requires a good dispersion of the mixing energy over the entire volume. According to Harnby et al. (1992b), an axial flow is recommended for this. In limited reservoirs axial flows can be created with so-called "marine blade impellers", depicted in Fig. 2A. Due to the design with constant pitch ratios, marine blade impellers cause an axial velocity increase. The flow is deflected by the walls of the reservoir creating circular flows over the entire volume (see Fig. 3A). Determining a reproducible reference state for the degree of homogeneity is difficult because homogeneity is hard to monitor during conditioning. Therefore, perfect homogeneity should be aimed for. Assuming that the degree of homogeneity improves with the duration of axial mixing, the minimum duration must be determined to achieve this goal. In preparation for the settling and consolidation experiments of this study, mixing times of 15 min, 30 min and 45 min are therefore applied.

2.1.2. Floc breakup by radial mixing

Floc breakup occurs when shear stress exerted on the floc exceeds the floc shear strength. Such shear stress can be induced on the flocs through flow and inter-particle collisions (Mehta, 2014). In nature, turbulent flows can already induce sufficient shear stress for floc breakup (Manning, 2004), indicating the low shear strength of flocs. This makes it unrealistic to assume floc breakup can be controlled during mixing. Hence, the only reproducible reference state that can be achieved by mixing is that in which all flocs are broken. According to Harnby et al. (1992b), shear is created by radial flows (see Fig. 3B), which in turn are induced by mixing with so-called "paddle impellers", depicted in Fig. 2C. Given the low shear strength of flocs, it can be assumed that the duration of radial mixing can be limited. Nonetheless also 15 min, 30 min and 45 min of radial mixing are applied in preparation of the experiments.

2.1.3. Hybrid mixing

By applying only the two extremes of mixing (axial and radial), the level of impact of each can be demonstrated. However, both are probably required as stated earlier. A combination of the two is therefore also applied. This was tested in two ways. The easiest way is to use a "pitched blade impeller", depicted in Fig. 2B. The angle in which the blades are pitched determines the dominant flow type. The angle of the pitched blade impeller used in this research is $\frac{\pi}{4}$ rad. It is however unknown if the distribution of energy at this angle is correct to achieve both intended reference states. Therefore, a second combination method is used in which both extremes are applied in succession. First the mud is conditioned with radial mixing, followed by axial mixing. Because the impact of the duration for radial mixing is assumed to be limited, this was only done for 15 min, while axial mixing was performed for 30 min, 45 min and 60 min. For practical

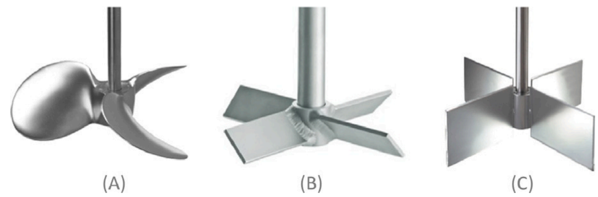

Fig. 2. Mixing impellers ordered from low shear (left) to high shear (right). (A) Marine blade impeller; (B) Pitched blade impeller; (C) Paddle impeller.

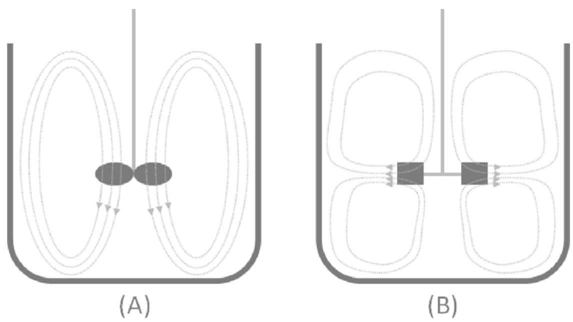

Fig. 3. (A) Axial flow for homogenisation; (B) Radial flow for shearing.

reasons, the pitched blade impeller is used in this combination for the radial mixing, rather than the paddle impeller. After all, due to the low shear strength of cohesive flocs it is assumed that the shear intensity produced by a pitched blade impeller is already sufficient to break all cohesive flocs.

2.2. Setup and instrumentation

2.2.1. Consolidation columns

Plastic tubes of 2 m in length, an outer diameter of 63 mm and a wall thickness of 3.2 mm were used as settling columns. Nine of them were mounted together in a fixed upright position. Backlighting is used to accentuate the water–mud interface. For this purpose, four double fluorescent tubes of 1.2 m are mounted behind the columns. In between a plastic light diffuser panel is installed for optimal spreading of the light. A recorded image illustrating the results of this setup is depicted in Fig. 4.

2.2.2. Automated interface level recording system

An IDS uEye USB camera, type UI-3200SE-C-HQ camera is used to simultaneously record the water–mud interface levels of all nine columns. The camera was equipped with a colour sensor having a resolution of 4104 by 3006 pixels. It was mounted at a distance of 6.5 m from the columns. With a fixed focal lens of 35 mm this results in a field of view of approximately 2258 by 3468 pixels. The resolution was approximately 0.63 mm per pixel. Image acquisition was managed with an in-house software application. To manage the amount of data, the acquisition frequency was variable throughout the experiment. The time intervals for these experiments varied from 15 min at the start of the experiment (high settling rates — see Fig. 1) to 2 h at the end (low settling rates — see Fig. 1).

2.2.3. Image processing

The image processing software is programmed in LabVIEW, which has an extensive image processing library. For this application, the "straight edge detection" algorithm is used to detect the water–mud interface. This algorithm searches for a transition from bright to dark (or vice versa) along search lines within a defined region of interest. This outputs a list of points (edges) through which the algorithm fits a line. This line is considered to be the water–mud interface. With the

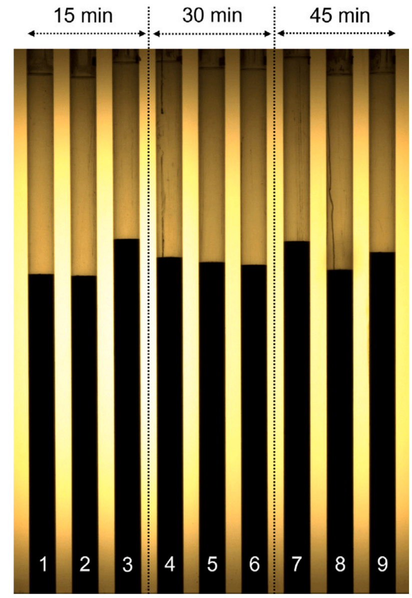

Fig. 4. A picture of the nine consolidation columns during consolidation tests. Each series of experiments consisted of three columns with mud conditioned for 15 min (columns 1, 2 and 3), 30 min (columns 4, 5, and 6) and 45 min (columns 7, 8, and 9). With backlighting the water–mud interface is accentuated.

backlighting, the contrast between the dark opaque mud and the bright transparent water is high enough to ensure robust edge detection.

2.2.4. Particle size distribution

For each experiment, an attempt was made to analyse the size of the flocs after conditioning. A sample was taken while the mud was pumped into the columns. These samples were analysed using a Malvern Mastersizer 2000 (Malvern Instruments, 2007). This device is used to perform particle size distributions based on laser diffraction in the Mie scattering regime. Although laser diffraction is a well-known technique to analyse floc sizes (e.g. Krishnappan, 2006; Hill et al., 2011), the results of the analyses during this study did not indicate any significant differences in particle size distribution between the different samples. There are, however, important differences in setup compared to Krishnappan (2006) and Hill et al. (2011). In these studies, the laser diffraction setup was placed in the experimental setup or on-site, i.e. where the flocculation or floc break up occurred. This is not possible with the Malvern Mastersizer 2000, hence the sampling. From the samples, a small subsample is suspended in a beaker with water kept in motion with a rotating impeller to prevent settling of the particles. This highly diluted mud sample is circulated in the apparatus where laser diffraction is applied in a section of transparent tubes. Due to the fragility of the flocs, each of these intermediate steps is likely to lead to further break up of any flocs present. Thus, despite the initial differences in the presence of flocs, the particles present in each sample become similar prior to the laser diffraction analysis, which explains the similar results. The output of these analyses should therefore be considered as a particle size distribution when hardly any flocs are present in the mud. Fig. 5 shows a plot representing the volume distributions of particle sizes present in different samples. This plot shows two sets of curves, one where the sample is analysed as is, and one where the sample is exposed to high-intensity ultrasound before analysis. Ultrasonic treatment is a function of the Malvern Mastersizer 2000 to facilitate the dispersion of particles in a sample. Alternatively, it can also be used to break up flocs (Malvern Instruments, 2007). When the results after ultrasonic treatment are considered as results with no flocs present, the slight difference between the two sets of curves feeds the previous presumption that additional flocs are broken during processing by the Malvern Mastersizer 2000, resulting in similar amounts

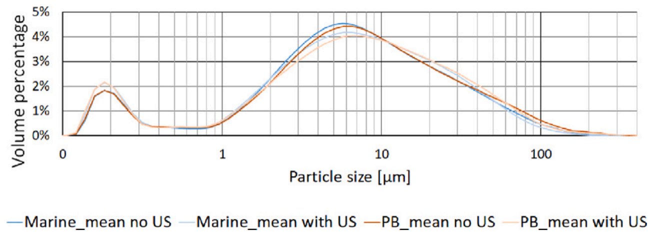

Fig. 5. Mean particle size distribution curves after mixing with the marine impeller and the pitched blade impeller, both without and with ultrasonic treatment. As elaborated in Section 2.2.4 these curves should be considered as particle size distribution curves when hardly any flocs are present in the mud.

and sizes of flocs. Therefore, to compare the differences between the mud after conditioning with the different mixing techniques, the results of these particle size analyses are not used.

3. Experimental methodology

3.1. Conditioning procedure

The mud used originates from the Zeebrugge docks of the Port of Antwerp-Bruges, Belgium. Being North-Sea mud, the gel density is known to be about 1.10 g cm^{-3} (Meshkati Shahmirzadi et al., 2015). A batch was collected from maintenance dredging and transported to the laboratory of Flanders Hydraulics (FH) in Antwerp. The mud was transported, stored and conditioned in barrels of approximately 65 l, made of HDPE. During transport and storage, the barrels were sealed airtight, while the HDPE prevented any light penetration, minimising any activity of the organic fraction. Two barrels of mud were prepared and alternately used per experimental series. During the project, the barrels were stored and processed indoors at a more or less constant temperature of 15 °C to 20 °C. A day before the start of the experiments the mud was prepared to the intended density of 1.08 g cm^{-3}. For the first experiments, the mud was diluted. This was done with seawater obtained from the same location as the mud to preserve the salinity of the mud. With each experiment, some of the consolidated mud was lost as it stuck to the wall of the columns. In preparation of subsequent experiments, the mud thus had to be thickened. This was done using mud from the delivered batch of mud from which the two different batches were prepared earlier.

Diluting and thickening were performed using the same conditioning setup as for the experiments themselves, illustrated in Fig. 6. The setup consists of a stationary mixer to allow for long mixing durations and a closed pump circuit, including a continuous density measuring device (Anton Paar DPRN 427). During conditioning, the rotational speed of the mixers was set as high as possible to maximise mixing intensity (Harnby et al., 1992b). However, the speed was limited to avoid spillage due to excessive turbulence. The impellers used were already available, so their dimensions were not optimised for the size of the reservoir in which mixing was performed. After all, according to Harnby et al. (1992a), the optimum impeller diameter is 25% to 66% of the inner diameter of the reservoir, which is about 35 cm. With diameters of 24 cm, 30 cm and 13 cm for the marine impeller, pitched blade impeller and paddle impeller, respectively, especially the pitched blade impeller falls outside this recommendation. All impellers were placed at a height from the bottom of about 10% to 20% of the height of the barrels, while the barrels were completely filled except for a practical margin. While mixing, vortexing should be avoided, as this causes air entrapment. The presence of air in mud is unwanted, as air bubbles will rise when the mud is at rest, affecting the sedimentation and consolidation process. To prevent gross vortexing during mixing, two baffles are installed (Harnby et al., 1992a). Ideally there should be four, one per quadrant. However, due to practical limitations, the baffles were fixed to the frame of the mixer, allowing only two. After the mud was prepared to the desired density, it was left to rest until the start of the actual experiment the next day (about 21 h later). This way, the initial state of the mud at the beginning of each experiment, starting with conditioning, can be considered similar for all experiments. Upon conditioning, the mud is pumped around in a closed circuit to verify the density using a continuous density measurement device (Anton Paar DPRN 427). A peristaltic pump is used to prevent changes in the composition of the mud due to pumping (e.g. breakup of flocs). Meanwhile, the escape of any entrapped air is facilitated by low-intensity mixing. After a few minutes, the discharge hose from the pump is brought to almost the bottom of the column through the open top. During filling, the discharge hose is retracted while it remains just below the mud surface. On average the columns were filled to 1605 mm (varying from 1521 mm to 1695 mm).

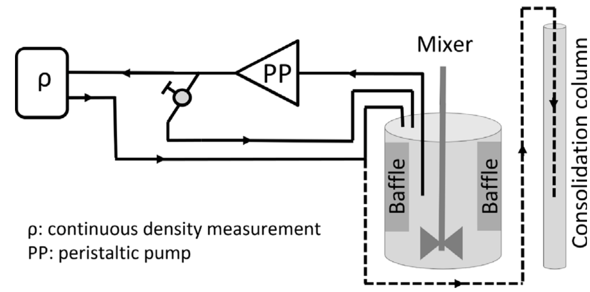

Fig. 6. Schematic overview of the mud conditioning setup as used during the experiments. The barrel and mixer were fixed to allow for long mixing durations. Two baffles were installed opposite to each other and fixed to the frame of the mixer. The density is checked using a continuous density measurement device (Anton Paar DPRN 427) in a closed pump circuit (solid lines). Once the mud was considered to be ready the closed circuit was broken and the discharge hose replaced to the columns (dashed lines).

3.2. Experimental programme

One series of experiments consists of nine settling and consolidation experiments, as shown in Fig. 4. The mud from each experiment within a series comes from the same batch of mud, conditioned with one of the four mixing techniques discussed in Section 2.1. Three replicated experiments are set up per mixing duration, yielding the nine experiments per series. Each of these series was repeated three times, resulting in a total of twenty-seven settling and consolidation experiments per mixing technique. This programme is summarised in Table 1.

Halfway through the experiment of the series with the pitched blade impeller mud started to stick to the inner walls of the columns. Suspectedly this was caused by calcareous deposits on the inner walls of the settling columns during the experiments. Because of this, it was impossible to detect the water–mud interface as elaborated in Section 2.2.3. The tubes were cleaned with calcium solvent and the series of the pitched blade impeller was repeated. The valid recordings of the first attempt are however also taken into account when processing the results.

As mentioned in Section 3.1, the targeted initial density was 1.08 g cm^{-3}. In practice, an interval of 1.079 g cm^{-3} to 1.081 g cm^{-3} was allowed. The densities of the second series with the combination of pitch blade and marine impeller exceeded the upper limit. Therefore, an additional fourth series was carried out.

4. Experimental results & discussion

4.1. Averaged settling curves

With the recorded water–mud interface levels, the settlement of the water–mud interface is calculated at each timestamp of a recording

Table 1
Summary of the test programme for each mixing technique. Each series of tests per mixing technique was repeated three times, unless stated otherwise in Section 3.2. The indicated settling column numbers refer to the columns depicted in Fig. 4.

Mixing impeller	Mixing time duration [min]	Settling columns
Marine	15	1, 2 and 3
	30	4, 5 and 6
	45	7, 8 and 9
Pitched blade	15	1, 2 and 3
	30	4, 5 and 6
	45	7, 8 and 9
Paddle	15	1, 2 and 3
	30	4, 5 and 6
	45	7, 8 and 9
Pitched blade + Marine	15 + 30	1, 2 and 3
	15 + 45	4, 5 and 6
	15 + 60	7, 8 and 9

as the difference between the level recorded at the corresponding time and the starting level of the experiment. With these values of settlement a settling curve can be plotted for each experiment. Because the starting levels of the experiments are not exactly the same, both the settling scale and the time scale have to be scaled to allow comparison between the different experiments. The settling scale is converted into a relative scale by expressing it as the ratio of the recorded interface level (h) relative to the initial levels (h_0) of the experiments, i.e. around 1605 mm (see Section 3.1). The time scale of the settling curve of each experiment is scaled by a scale factor equal to the ratio between the starting level of the experiment (h_0) and the starting level of a fixed reference experiment ($h_{0,ref}$). The starting level of one of the experiments was selected as this reference level. Average settling curves are calculated per mixing technique and duration across the different series of experiments. Plots of these averaged settling curves are shown in Fig. 7. These plots already show that when the mud is mixed using the combination of the pitched blade and marine impeller, the mixing time has a minor effect and even can be neglected.

Based on the typical shape of a settling curve (see Section 1.2) the start and end of the hindered settling phase is determined for each of the averaged settling curves. Since the start of the hindered settling phase corresponds to the end of the linear settling phase, this moment can be determined as the point where the settling curve starts to deviate from the linear trendline fitting the settling curve during the settling phase. The end of the hindered settling phase corresponds to the start of the consolidation phase, which, in the case of a well-homogenised suspension of cohesive sediments, occurs when the bulk density approximates the gel density. Since a continuous structure is formed from this moment, the point on the settling curve indicating this transition can be accurately determined from the effective stress, which can be calculated as the difference between the total stress and the pore water pressure (Toorman, 1996). Both these parameters, however, require additional measurements, which were not conducted during the sedimentation experiments of this study. For this study, the determination of this moment is therefore approximated by a similar method as for the determination of the beginning of the hindered settling phase. The end of the hindered settling phase is determined as the moment when the difference between the settling curve and a power trendline (Toorman and Leurer, 2000) fitting the settling curve during the consolidation phase becomes minimal. This procedure is illustrated in Fig. 8. The resulting timestamps and corresponding settlement values at the beginning and the end of the hindered settling phases are presented in Fig. 9 and Table 2.

4.2. Influence of mixing technique & duration

The results presented in Fig. 9 and Table 2 allow to evaluate the influence of the applied mixing techniques and mixing durations on the settling curves. Because the effect of the conditioning procedures may be different for each sedimentation phase, the observations for each sedimentation phase are discussed separately.

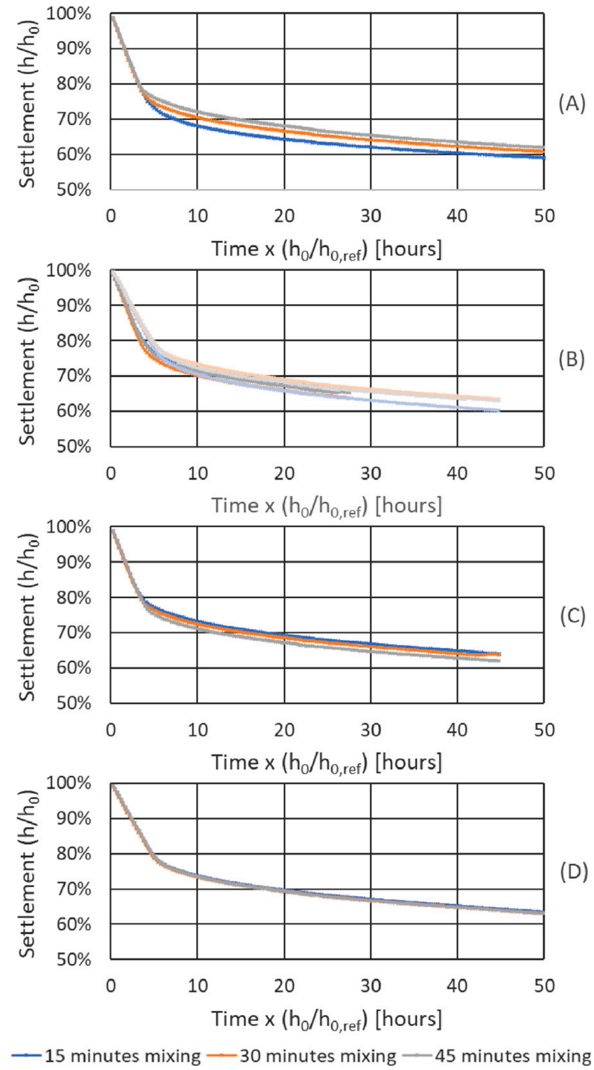

Fig. 7. Across the different test series averaged settling curves, sorted per mixing impeller (Fig. 2): (A) Marine impeller, (B) Pitched blade impeller, (C) Paddle impeller, (D) Combination of pitched blade and marine impellers. The settling is expressed relatively and the time scale scaled with h, h_0 and $h_{0,ref}$ as defined in Section 4.1. As mentioned in Section 3.2, two experimental series have been conducted with the pitched blade impeller (B). The results of the first series are plotted similar as in the other charts, while the results of the second series are plotted in the corresponding faded colour. The blue, orange and grey colours represent the shortest, middle and longest mixing durations (see Table 1), respectively. Each curve is averaged over at least nine experiments in accordance to Section 3.2 and Table 1.

4.2.1. Settling phase

The results presented in Fig. 9 and Table 2 show that the settling rate during the settling phase is lowest after conditioning by sequential mixing with the pitched blade and marine impellers. The highest settling rate is recorded during the experiments after mixing with only the marine impeller. A difference in settling rate is caused by a difference in the settling gradient or the duration of the settling phase, or both.

The duration of the settling phase during the experiments after conditioning with the paddle impeller show an increase with increasing mixing time. Since the paddle impeller induces mainly radial flows, which in turn induce shear stresses, this prolongation of the settling phase can be attributed to the extent of floc disintegration. After all,

Table 2

Resulting duration and progress of settlement during the settling phase and the hindered settling phase of the various average settling curves presented in Fig. 7. The method to determine these results are described in Section 4.1 and illustrated by Fig. 8. The results are represented by the markers in Fig. 9. For the settling phase the constant settling rate is provided with an accuracy of 0.63 mm s^{-1}.

Mixing impeller(s)	Settling phase			Hindered settling phase	
	Duration [h]	Settlement [%]	Settling rate [mm h^{-1}]	Duration [h]	Settlement [%]
Marine (15 min)	3.25	20.23	104	4.75	10.34
Marine (30 min)	2.50	16.20	108	6.50	12.75
Marine (45 min)	2.75	17.21	104	7.75	10.99
Pitched blade_series 1 (15 min)	2.25	12.76	92	3.50	11.65
Pitched blade_series 1 (30 min)	2.75	16.45	96	2.75	9.45
Pitched blade_series 1 (45 min)	3.00	17.01	91	2.50	7.56
Pitched blade_series 2 (15 min)	3.50	15.73	68	3.75	11.20
Pitched blade_series 2 (30 min)	3.75	16.31	70	3.50	8.33
Pitched blade_series 2 (45 min)	4.25	17.71	68	2.75	7.37
Paddle (15 min)	2.50	15.04	95	2.00	7.07
Paddle (30 min)	3.00	18.43	96	1.50	4.56
Paddle (45 min)	3.25	19.52	94	1.50	4.78
Pitched blade & marine (30 min)	4.50	19.30	68	1.50	3.55
Pitched blade & marine (45 min)	4.25	18.39	69	1.75	4.79
Pitched blade & marine (60 min)	4.50	18.96	67	2.75	5.42

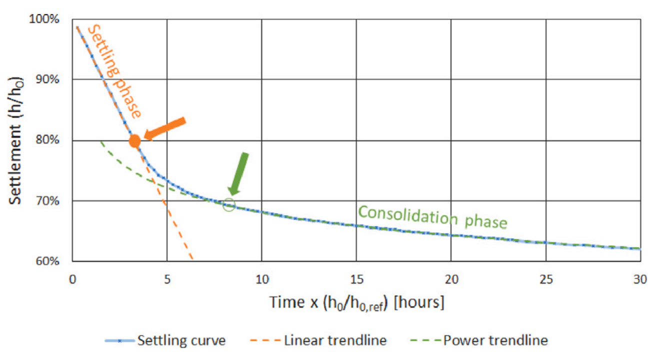

Fig. 8. Illustration of the procedure to calculate the start and end of the hindered settling phase of a settling curve as described in Section 4.1. The settling curve is plotted in blue. A linear trendline (dotted orange line) and a power law trendline (dotted green line) are determined fitting the settling phase and the consolidation phase, respectively. The beginning of the hindered settling phase is determined as the moment where the divergence between the settling curve and the linear trendline increases. The end of the hindered settling phase is determined as the moment where the divergence between the settling curve and the power law trendline becomes minimal.

when cohesive flocs are broken into smaller flocs or even particles, these smaller flocs or particles must first merge back into larger flocs, corresponding the new low energetic condition in the column, before they will settle (see Section 1.5). Hence, settling is delayed and the settling phase prolonged. Increasing duration with increasing radial mixing time implies that the extent of floc breakup increases with radial mixing time. Since large cohesive flocs are considered to be weaker than small flocs (Serra and Casamitjana, 1998; Maggi, 2005), it can be assumed that further break up of flocs requires an increasingly higher shear stress as the size of the flocs decrease. As long as the shear stress induced by mixing exceeds the shear strength of the flocs, floc break up continues. Similar durations and increase in duration with increasing mixing time are observed after conditioning with only the pitched blade impeller, confirming the floc break up capacity of the pitched blade impeller. Although not the envisaged objective of axial mixing, the similar duration of the settling phase after conditioning with only the marine impeller implies that floc break up also occurs during axial mixing. After all, shear stresses are inevitable during high turbulent mixing, regardless of the type of dominant induced flow. When maximising mixing intensity, it is therefore reasonable to assume that the turbulence during mixing is much higher than the turbulence level from where floc breakup occurs (van Leussen, 1994; Dyer and Manning, 1999). Moreover, further additional shear is induced when the flows collide with the baffles (see Section 3.1). An increasing duration of the settling phase with increasing axial mixing time cannot be observed. Consistent with the aforementioned relationship between the shear capacity of the mixing technique and the size of the remaining flocs after mixing, it can be concluded that for axial mixing, the induced shear stresses are limited and the maximum floc disintegration is obtained already after short-term mixing. Further breaking of the flocs by extending the mixing time is thus not feasible. Nonetheless, the small difference in duration of the settling phase compared to the other experiments shows that the difference in size of the residual flocs can be considered small.

Following the above, it is surprising that the durations of the settling phase of the experiments after sequential mixing with the pitched blade and marine impellers stand out. Since the floc breaking capacity of the marine impeller is considered to be lower than that of the pitched blade impeller, this excessive duration cannot be attributed to the size of the remaining flocs and can thus solely be ascribed to the subsequent axial mixing. The effect of axial mixing on the settling behaviour during the settling phase is more visible in the settling gradients (Table 2, column 3). On average, the settling gradients of the experiments after conditioning where the marine impeller was used, whether in combination with another propeller or not, were larger than in the other experiments. As discussed in Section 2.1, mixing with the marine impeller is expected to induce axial flows enhancing the homogeneity of the mud. Perfectly homogeneous mud implies equal dispersion of cohesive flocs and coarse particles throughout the entire mud volume, resulting in a uniform density profile across the mud column. On the other hand, when a perfectly homogeneous mud is not achieved, the concentration of dense coarse particles will be higher at the bottom and lower in the upper layers and vice versa for the light cohesive particles. This results in a sloping density profile across the mud column. Consequently, the settled particles and flocs in the initial upper layers are denser as homogeneity increases, leading to higher effective stresses as they settle and consequently greater compaction and hence settling.

In case of similar floc size, and thus similar floc settling velocity, a greater settling gradient results in an extended settling phase. In the case of a combination of axial and radial mixing, the extension of the settling phase caused by both mixing techniques add up, resulting in the excessive durations. This also explains the unexpected similar, or even longer, durations of the settling phase after mixing with only the pitched blade impeller compared to those after mixing with only the paddle impeller. After all, the floc breaking capacity of the pitched blade impeller is considered to be less. Since the pitched blade impeller also generates axial flows which enhance homogeneity, the duration of the settling phase is also extended twofold. That the elongation is less pronounced compared to the experiments after sequential mixing with

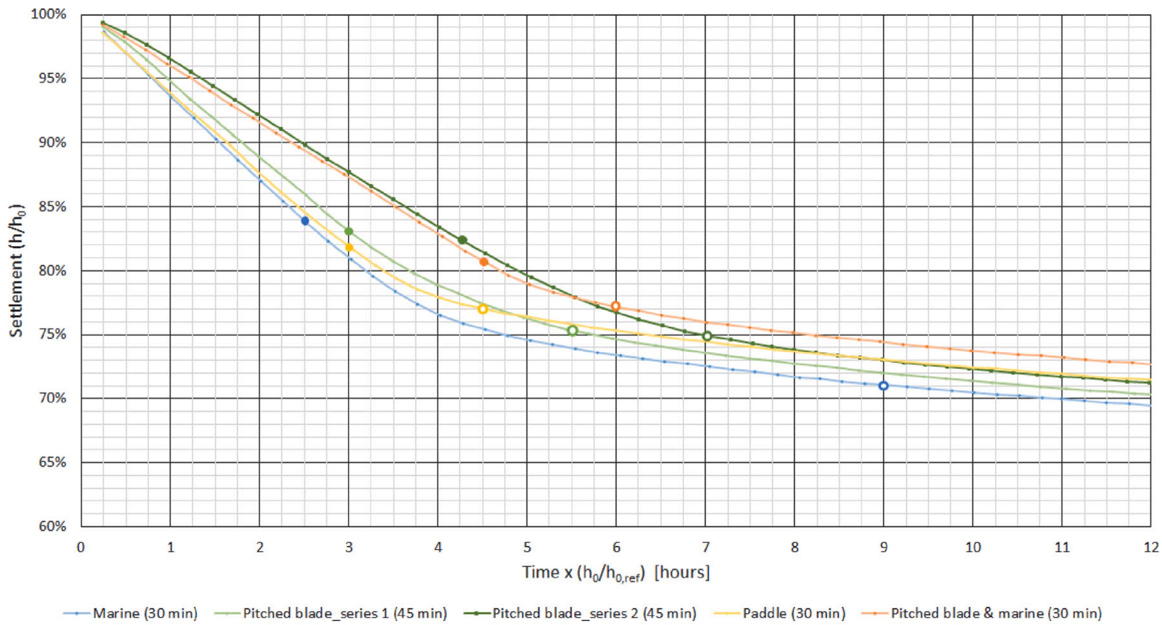

Fig. 9. Close-up on the settling phase and hindered settling phase of the different average settling curves for each conditioning technique. For the legibility of the figure and because the mixing time has only a minor effect (see Fig. 7), solely the intermediate curve is plotted for each conditioning technique. The start times of the hindered settling phase are indicated by the filled markers and the end times by the unfilled markers, in correspondence with Table 2.

the pitched blade impeller and the marine impeller can be attributed to either the shorter mixing times or lower homogenising capacity of the pitched blade impeller compared to the marine impeller.

4.2.2. Hindered settling phase

Overall, the longest durations and settling gradients of the hindered settling phase are recorded during the experiments following axial mixing using only the marine impeller. Added to the values of the settling phase, this leads to the most elapsed time and greatest settling at the beginning of the consolidation phase. Hence, it can be concluded that an increase in homogeneity postpones consolidation. The consolidation phase is initiated when a higher density threshold is reached. This density is earlier attained when the local concentration of heavy particles is higher. As mentioned in Section 4.2.1, an increase in homogeneity leads to a higher density in the upper layers and lower density in the lower layers. An enhanced homogeneity therefore creates a setback in density development in the lower layers and consequently delays the initiation of the consolidation phase. The observation that the duration and, to a lesser extent, the settling gradient increase with increasing axial mixing time emphasises this conclusion and implies that the maximum homogenising capacity is not yet achieved.

This increase in duration and settling gradient with increasing axial mixing time can also be observed after sequential mixing with the pitched blade and marine impellers. In contrast, however, the values of both are the lowest of all experiments. This is remarkable since for these experiments, the settling gradients during the settling phase, are among the largest (see Section 4.2.1). Despite the settling gradients during the settling phase of the experiments after axial mixing with only the marine impeller being similarly high, this similarity is no more during the hindered settling phase. This reversal must therefore be caused by the higher floc breaking capacity of the preceding mixing with the pitched blade impeller. This is confirmed by the decreasing settling gradient with increasing radial mixing time during both the experiments after mixing with the pitched blade impeller and those after mixing with the paddle impeller. The duration of and the settling gradient during the hindered settling phase after mixing with the paddle impeller, however, are lower than after mixing with the pitched blade impeller. This confirms the presumed lower floc breaking capacity of the pitched blade impeller compared to the paddle impeller, as concluded in Section 4.2.1. The decrease in settling gradient is thus proportional to the extent of floc breakup during conditioning. After all, floc breakup leads to delayed settling of cohesive flocs during the settling phase, as discussed in Section 4.2.1. While, other non-cohesive and more dense particles will settle almost instantly and faster. This difference in settling behaviour leads to segregation between the two (van Ledden, 2003; Winterwerp and Van Kesteren, 2004). In turn this will lead to less dense cohesive flocs (Toorman and Berlamont, 1993; Torfs et al., 1996) and therefore lower effective stresses when settled. Consequently, the settled layer of cohesive flocs will be less compact, resulting in a lower settling gradient. This is comparable to the difference in compaction when dumping dredged mud in water or on land. When dumped in water, the high-density mud will mix with water, resuspend and dilute, causing segregation. When dumped on land the density is maintained and the sand remains trapped in the cohesive flocs. Therefore, the cohesive flocs are denser which is beneficial for compaction and the settling rate (Toorman and Berlamont, 1993).

4.3. Repeatability

As mentioned in Section 2.1, repeatability of settling curves involves the ability to reproduce reference states by conditioning the mud. Section 4.2 concludes that such a reference state for floc size is most efficiently achieved by radial mixing. Axial mixing in mud, in turn, approximates the reference state of absolute homogeneity with increasing mixing durations. Since the settling behaviour of mud is determined by both the size of the flocs and their dispersion in the mud volume, reference states for both floc size and homogeneity must be achieved through mud conditioning. As discussed in Section 4.2, this is most effectively achieved by sequentially applying radial and axial mixing.

To objectify the level of repeatability between experiments, the standard deviation of the settling curves of those experiments is calculated along their time scale, i.e. for each timestamp the standard deviation of the corresponding settling values is calculated. Low values of standard deviation indicate good repeatability and vice versa. For each combination of applied mixing impeller and duration, the repeatability is assessed per series and across the different series. Each series consists of three of the same experiments (see Section 3.2). Thus, to assess repeatability for each series, standard deviations of those three experiments are calculated (Eq. (1)). To assess the repeatability across the different series, all experiments of the applicable combination of applied mixing impeller and duration are considered (Eq. (2)). Including intermediate conditioning and use of mud from different batches, the latter best simulates the execution of hydraulic experiments for nautical research. Hence, it is the main goal of this research to improve the repeatability across the different series. In addition, repeatability is differentiated for each sedimentation phase by determining the mean standard deviation over the corresponding time frame of the sedimentation phase as determined in Section 4.1 and Fig. 8. The mean standard deviations per series are presented in Fig. 10. Those for the analysis across the different series are presented in Fig. 11.

$$\overline{\sigma}_{t,\text{per series}} = \frac{1}{3}\sum_{s=1}^{3}\sqrt{\sum_{e=1}^{3}\frac{(X_{s,e,t}-\overline{X}_{s,t})^2}{3}} \tag{1}$$

$$\sigma_{t,\text{across series}} = \sqrt{\sum_{s=1}^{3}\sum_{e=1}^{3}\frac{(X_{s,e,t}-\overline{X}_{s,t})^2}{9}} \tag{2}$$

where $\overline{\sigma}_{t,\text{per series}}$ is the mean of the standard deviations at timestamp t of three repetition experiments within a series, $\sigma_{t,\text{across series}}$ is the standard deviation at timestamp t across the different series of experiments, X is the relative settlement of the water–mud interface (Section 4.1) and the indices e and s refer to the different experiments and series, respectively.

4.3.1. Repeatability of experiments per series

The results depicted in Fig. 10 show that the maximum standard deviations of most series are below or around 1%. Two series using the marine impeller show higher values, but still below 2%. Compared to the repeatability of previous studies (see Section 1.3), this is already a significant improvement, which can be attributed to the strict procedural conditioning following a fixed duration of mixing and constant mixing intensity. Indeed, this was not always the case in the previous studies, as elaborated in Section 1.4.

It is also noticeable that the repeatability is slightly better for the experiments following radial mixing. Within a single series of experiments, mud is used from one and the same conditioned batch. Thus, the degree of homogeneity of the mud is the same for all experiments and therefore becomes irrelevant when comparing the settling behaviour of the experiments within the same series. Consequently, only a difference in particle size can cause any deviating course of the settling processes. Because a higher floc breaking capacity provides more control over the residual floc sizes, the behaviour of radially mixed mud is more uniform within a single series of experiments. Nonetheless, the difference with the repeatability of the experiments after axial mixing with only the marine impeller is not significant. This confirms the slightly lower floc breaking capacity of axial mixing.

4.3.2. Repeatability of experiments across series

Fig. 11 shows the standard deviations of the mean settling curves, averaged across the multiple series of three experiments. This simulates the conduct of a series of hydraulic experiments using mud, such as for nautical research (see Section 1.1). With an overall standard deviation of about 1% to 2%, the combination of axial and radial mixing yields the highest repeatability throughout the full course of the experiments. There is no significant difference between the simultaneous combination using only the pitched blade impeller and the combination using sequentially the pitched blade impeller and the marine impeller. Again, this is a significant improvement over previous studies (see Section 1.3).

The repeatability of the experiments after radial mixing with the paddle impeller achieves the same high level as the experiments after the combination of axial and radial mixing, only during the settling phase. This shows that the course of the settling phase is mainly governed by the residual size of the flocs after conditioning. Although slightly divergent, the various mixing techniques used all do have a significant capacity to break up flocs (see Section 4.2). So for all experiments, floc size variation was always more or less under control, resulting in high repeatability of all experiments during the settling phase. Since axial mixing with the marine impeller is considered to have the lowest floc breaking capacity, a longer mixing time is required to achieve comparable high repeatability.

Starting from the hindered settling phase, the further course of sedimentation and consolidation is governed more by the initial degree of homogeneity of the mud. This is reflected in the lower repeatability of the experiments after radial mixing with the paddle impeller, which has no significant homogenising ability. (see Section 4.2). As a result, in the case of mud of like composition, the behaviour during the hindered settling phase is similar for each experiment when a mixing technique with homogenising capacity is applied during conditioning.

The levels of repeatability during the consolidation phase are very similar to those during the hindered settling phase. Therefore, it can be concluded that neither initial floc size distribution nor initial homogeneity further influence the sedimentation process once the hindered sedimentation phase is passed. This confirms the statement that a difference in settling curve develops mainly during the settling and hindered settling phases. (see Section 1.3).

5. Conclusions and recommendations

The importance of procedural conditioning of mud is reported in various published studies. Yet a uniform procedure was never suggested. The results of this study not only confirm the importance of procedural conditioning, but also show that the applied mixing technique during conditioning affects the settling behaviour of the mud. Therefore, to allow comparison between different studies and improve the reproducibility of mud behaviour, a conditioning procedure containing a combination of both axial and radial is proposed for any experiment involving the behaviour of mud. Whether the combination of both mixing techniques is done simultaneously with one and the same impeller or sequentially through multiple impellers makes little difference in repeatability. For practical reasons, the use of one and the same impeller is preferred. A condition, however, is that both the floc breaking capacity and the homogenising capacity of the impeller are sufficient.

Radial and axial mixing enable the creation of reproducible reference states for particle size and homogeneity, respectively. This way, the initial state of the mud at the start of an experiment can be reproduced, thereby optimising the repeatability of the course of the sedimentation process of mud of like composition. Since particle size and homogeneity are difficult to measure or monitor during mixing, it was suggested (see Section 2.1) that such reference states can only be obtained by pursuing the extremes of these characteristics. For particle size, this means breaking up all cohesive flocs, leaving only unbound cohesive and non-cohesive particles. For homogeneity, this is somewhat less clear-cut and can only be aimed at the highest possible degree of homogeneity. The results of the experiments conducted during this study show that a minimum capacity for both is indeed required to have a positive effect on repeatability. However, if the maximum capacity of a mixing technique is insufficient to achieve the pursued extreme, the ultimate level achieved can also act as a reproducible reference state as long as the same equipment is used following the same procedure.

Overall, the combination of axial and radial mixing yields the best results for repeatability of mud settling behaviour. Depending on the conduct of the experiments or the sedimentation phase of interest, other procedures may also be adequate. For example, in the case of a one-off series of experiments with the same batch of mud, radial mixing alone can also be considered as an adequate mixing technique to

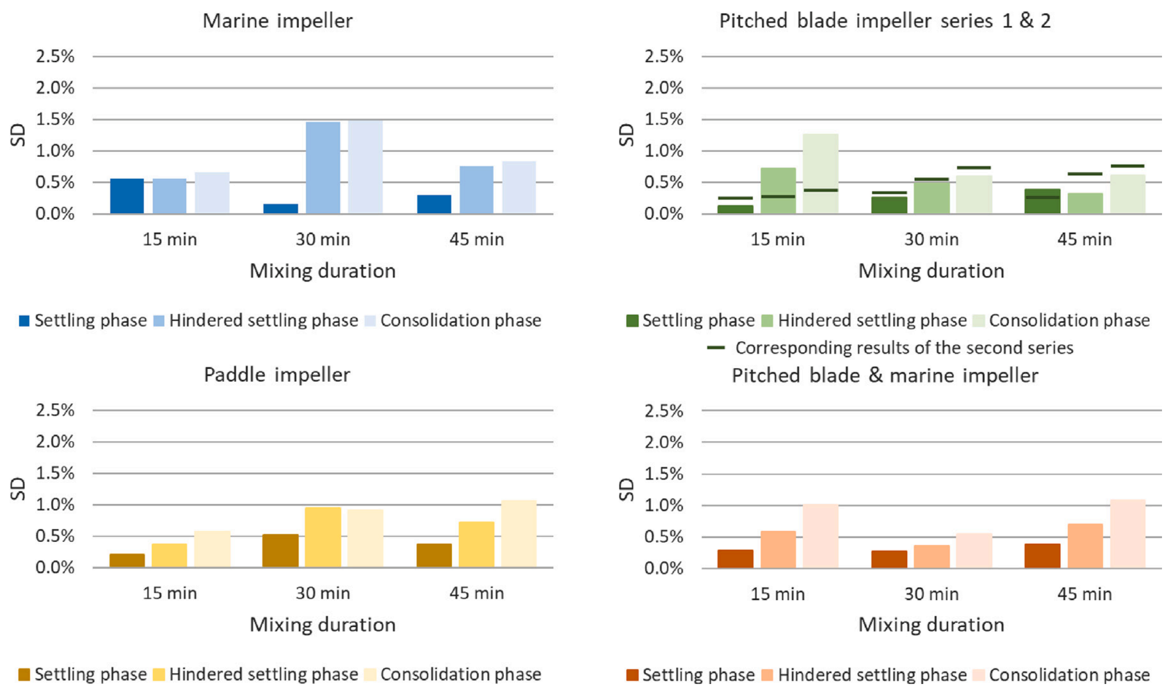

Fig. 10. Standard deviations (SD) of the settling curves averaged per series of three repetition experiments (see Section 3.2 and Table 1), sorted per mixing technique. The chart of the pitched blade impeller shows the results of both series performed with the pitched blade impeller (see Section 3.2). The results of the first series are presented with the bar charts. The results of the second series with the dark green lines aligned with the corresponding bar chart. For each mixing technique, a breakdown of the applied mixing duration and phases of settlement is provided.

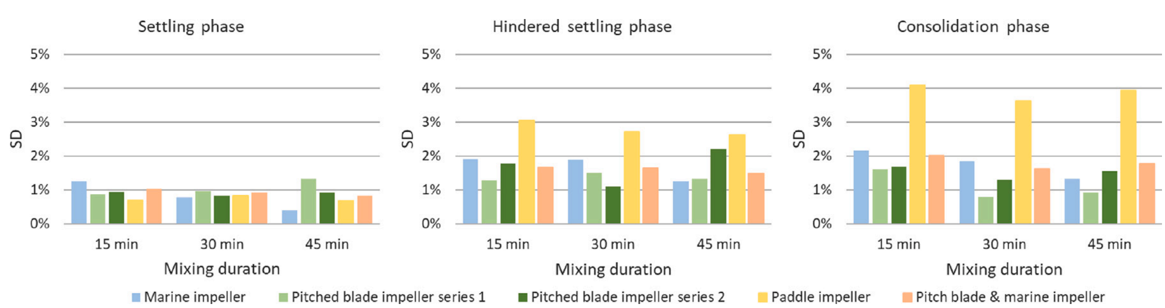

Fig. 11. Standard deviations (SD) of the settling curves averaged across the different series of three repetition experiments (see Section 3.2 and Table 1), sorted by phase of settlement. For each phase of settlement, a breakdown of the applied mixing duration and mixing technique is provided.

achieve optimal repeatability. For multiple series of experiments with different batches of mud of similar composition, either only axial or only radial mixing may be an option, if only the settling phase is of interest. Because of the limited time between mud conditioning and the conduct of experiments, the latter may be the case, for example, during laboratory experiments for nautical research as performed by Lovato et al. (2022) and Sotelo et al. (2022).

Furthermore, it is recommended to determine the minimum required duration of conditioning as a function of the conditioning set-up, mud composition and mud volume, because all these factors are likely to be influential. If such a preliminary assessment is not possible, it is advisable to maximise the duration of conditioning.

As a reminder, it should be noted that this study is limited to experiments with mud with an initial density below the gel density. Since the settling behaviour of mud with a density above the gel density is different, similar experiments with such mud are of interest to verify the conclusions of this study. However, the most ideal conditioning procedure is not expected to depend on the ratio of initial mud density to gel density.

CRediT authorship contribution statement

Bart Brouwers: Writing – original draft,Editing, Visualisation, Validation, Methodology, Investigation, Conceptualisation. **Dieter Meire:** Writing – review & editing, Methodology, Conceptualisation. **Erik A. Toorman:** Writing – review & editing. **Jeroen van Beeck:** Writing – review & editing, Supervision. **Evert Lataire:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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