New evidence for the origin and behaviour of deep ocean ‘crusts’

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ABSTRACT: In situ tests in deep water West African clays show crust-like shear strengths within the top few metres of sediment. Typical strength profiles show s_u rising from mud-line to 10kPa to 15kPa before dropping back to normally consolidated strengths by 1.5m to 2m depth. A Cam-shear device is used to better understand the mechanical behaviour of undisturbed crust samples under pipelines. Extremely variable peak and residual shear strengths are observed for a range of pipeline consolidation stresses and test shear rates, with residual strengths approximating zero. ESEM of undisturbed samples and wet-sieved samples from various core depths show the presence of numerous randomly-located groups of invertebrate faecal pellets. It is therefore proposed that the cause of strength variability during shear testing and, indeed, of the crust's origin, is the presence of random groups of faecal pellets within the sediment.

1 INTRODUCTION

1.1 *Background*

As oil and gas exploration continues to expand into deeper waters off the west coast of Africa, the phenomenon of deep sea clay crusts is becoming more familiar to industry and academic research. Installation of oil flowlines in these areas causes partial embedment into the crust material resulting in the need to understand the medium- and long-term behaviour of these sediments under hot pipeline conditions. Installed pipelines undergo several hundreds of thermal cycles during their operational life. Pipeline designers therefore require an understanding of the undrained shear strength (s_u), which governs depth of pipe embedment, and the soil-pipe coefficient of friction (μ) along axial sections of pipe adjacent to designed-in buckles, which governs the amount of self-weight anchorage.

1.2 *West African Clays*

The clays of interest lie in water depths of between 1000m and 2000m and exhibit very high water contents and liquid limits as shown in Figure 1. Organic matter content ranges from 3% to 6% (Thomas et al., 2005), representing an environment with a high level of organic input. The Benguela Current bringing nutrients from the Benguela Upwelling to the south may influence the areas of interest, as may the terrestrial input from the Congo River to the north.

The strength of the crust was initially identified through in situ cone penetration and T-bar penetration tests used to investigate proposed pipeline alignments. Typical undrained strength profiles are shown in Figure 1; values rise to 10kPa to 15kPa between 0.5m and 1m depth before reducing sharply.

Had the strength profile from Figure 1 been obtained from a terrestrial mud, the favoured geotechnical origin would have been shallow overconsolidation due to desiccation. This hypothesis is apparently not applicable in deep water.

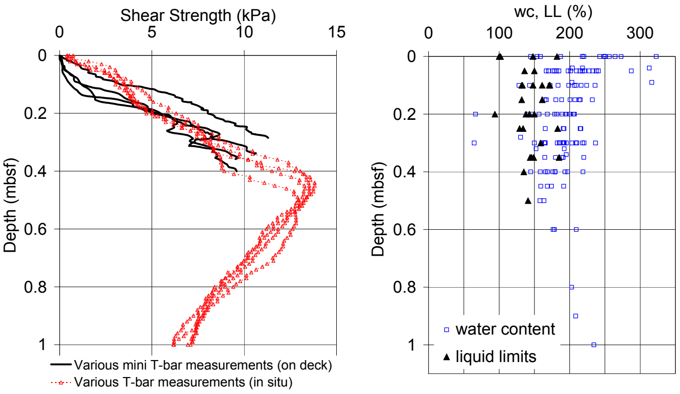


Figure 1. Typical shear strength profiles from T-bar testing and variation in water content with depth.

1.3 *The crust: hypothesis-testing*

Previous work in these sediments has cited “enhanced chemical activity of the upper layers” (De Gennaro et al., 2005 p1068) as a plausible explanation for the presence of crusts. Such activity may be in the form of chemical precipitation or osmosis (e.g. Ehlers et al., 2005; Sultan et al., 2001). Rigid cementation of the sediment by precipitates (chemical or biological) could result in increased sediment shear strength whilst maintaining high water contents. However, extensive microscopy during the current investigation has not identified any such precipitation.

Another possible explanation for the crust origin may be the presence of micro-organisms such as bacteria which are in great abundance in marine sediments. Bacteria may either be transported through the water column or be active within the sediment. Turley et al. (1995), Ransom et al. (1997) and Bhaskar and Bhosle (2005) consider the formation of aggregates within the water column by the production of extra-cellular polymeric substances (EPS), which may be produced by bacteria. Parkes et al. (2000) suggest that bacterial numbers may exceed 10^9 cells per cubic centimetre of sediment within the top metre. Their presence within the clay matrix may hypothetically influence sediment mechanical properties such as permeability and shear strength through the production of EPS. These studies have considered the water-sediment interface whereas the interest of the current investigation is material from significantly greater depth. By undertaking comparative shear tests on sterile and bacterially-inoculated samples, Kuo and Bolton (2009a) showed that the presence of the bacterium *Marinobacter aquaeolei* only had a minor influence on shear strength.

A third possibility is the presence of burrowing invertebrates which heavily populate the upper metres of deep ocean sediments. Offshore investigations undertaken by several authors highlight the influence of such organisms in both shallow and deep waters. Rowden et al. (1998) observed the presence of an increase in mean particle size due to the "aggregation of fine particles into faecal pellets" (Rowden et al., 1998 p1354). Meadows et al. (1994) completed a detailed examination of invertebrate bioturbation in cores taken from the central Southern Pacific Ocean at water depths from 5000 to 5300m. It was demonstrated that a significant number of open burrows ranging in diameter from 0.5cm to 4.5cm were present to at least 0.4m depth. Burrows were found to be oriented both vertically and horizontally, with the most abundant being the smallest diameter burrows. Undrained shear strength was measured using a Geonor fall cone penetrometer at 0.05m intervals down-core. Results from these tests showed a rapid increase in s_u in several test locations, with values of up to 12kPa at 0.4m depth. Variations in strength were attributed to the effects of bioturbation, whereas the increase in strength with depth was suggested by Meadows and Meadows (1994) to be the result of normal consolidation of the clay due to increasing vertical effective stress. The strengths measured by Meadows et al. appear to be similar to those in Figure 1, demonstrating a degree of overconsolidation. It is suggested that the effects of bioturbation may control the trend line of strength, not just the fluctuations. The current investigation suggests that faecal pellets from burrowing invertebrates may be the major contributing factor to increased sediment strength within the crust.

No hypothesis for the disappearance of crustal strength at 1m to 2m depth has yet been advanced. The following are suggested:

1. Crushing of pellets due to in situ vertical effective stress, equivalent to approximately 3kPa at 1m depth, resulting in 'resedimentation' of originally pelletised material; and
2. Continuation of biological activity with smaller organisms or bacteria breaking-down pelletised material into smaller agglomerates and/or removing mucin membranes, therefore allowing resedimentation.

If loss of crustal strength is associated with the breakdown of pellets with increasing depth, then a reduction in the percentage of pelletised material should be observed. Oedometer tests may provide evidence for crushing of pellets due to increasing vertical effective stress.

Previous laboratory shear testing of West African offshore clays was conducted on fully remoulded samples. They were reconsolidated to vertical effective stresses considerably higher than in situ values, and then allowed to swell under vertical stresses equivalent to those applied by a pipeline, prior to shearing. Undrained shear strengths approximated those found at shallow depth in the crusts.

Access to new undisturbed box core samples presented the opportunity to quantify the influence of sediment structure on shear strength and other mechanical properties within the crust, by comparing with remoulded and reconsolidated strengths. Visual inspection of undisturbed cores, with optical and microscopic imaging, also allowed quantification of the factors influencing sediment structure, including evidence of micro-organisms and of invertebrate activity. Environmental scanning electron microscopy (ESEM) and confocal microscopy may, for example, show the presence of polysaccharide (EPS) webs produced by bacteria within the crust, or the presence of mucous-derived membranes and macro-voids associated with bioturbated sediment. Optical microscopy, X-ray computer tomography (CT) and ESEM may also show the presence of bioturbation in the form of burrows and pelletised sediment.

The goal of this research is to provide evidence for the biological origin of deep ocean crusts, and to explain their mechanical behaviour in terms of their unusual natural structure.

2 METHODOLOGY

2.1 *Cam-shear testing*

To better understand the mechanics of the soil-pipeline interface, a series of interface shear tests were completed. The Cam-shear apparatus shown in Figure 2 was used to create stress and interface conditions for testing soil behaviour at shallow pipeline embedment. In addition to strength measurements, interface friction values for different pipeline coating roughnesses are of interest.

Shear tests were undertaken for vertical effective stresses of 2kPa to 6kPa using the following procedure:

1. Extrude undisturbed core sample from core liner and trim to 75mm diameter sample prior to extrusion into PTFE shear box;
2. Place shear box onto wet pipeline coating interface and seal around edge of box to permit only upwards drainage during consolidation;
3. Place interface material and sealed sample into waterbath before applying required vertical effective stress (equivalent to pipeline stress) via filter paper and porous disk; and allow to consolidate for at least 30 hours; and,
4. Interface material and shear box are removed from waterbath and attached to actuator for shear testing.

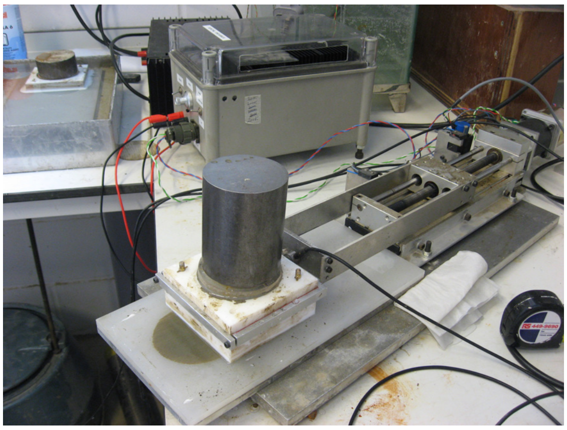


Figure 2. Cam-shear apparatus showing PTFE split-plane shear box, pipeline coating material and actuator.

Each sample was subject to three shear speeds: 0.05mm/s, 0.5mm/s and 0.005mm/s, corresponding to approximate descriptions of medium, fast and slow shearing. A shearing speed of 0.005mm/s was initially considered 'slow enough' to allow the determination of a 'drained' shear strength value. Internal (soil-soil) shear strengths were then measured by shearing at the split-plane of the shear box.

2.2 *One dimensional compression*

Two oedometer tests were undertaken on undisturbed samples from 0.25m and 0.3m depth to determine the preconsolidation stress and subsequent v-log p' behaviour. Sample fabric was imaged using ESEM and optical microscopy and the percentage of pelletised material determined prior to and after consolidation to observe the effect of vertical effective stress on the sediment structure, in particular, crushing of pelletised material.

2.3 *X-ray Computer tomography (CT) and ESEM*

To provide a three dimensional, non-intrusive image of core samples, an X-ray CT imager was used. This allows samples of up to 85mm diameter and 80mm height to be imaged while remaining within the core liner. The resolution that can be achieved with samples of this volume is limited. However, internal structure including burrows and macro-voids of millimetre scale can still be detected.

ESEM was used to image both fresh and autoclaved bulk samples and individual pellets in addition to pre- and post-test samples. All samples were imaged in moist conditions with vapour pressure and back scatter detectors to pick up secondary electrons.

3 RESULTS AND DISCUSSION

3.1 *Cam-shear test results*

Previous testing of reconstituted and reconsolidated samples undertaken by Bolton et al. (2007) suggested a good fit to the Cam-clay model proposed by Schofield and Wroth (1968). The results obtained from current testing of undisturbed samples are therefore also interpreted using the Cam-clay model as a framework. This allows a direct comparison and quantification of the influence of 'natural structure' present in undisturbed samples on the shearing characteristics of the samples.

Figure 3 shows the soil-soil results from Cam-shear tests on natural samples sheared beyond peak strength (to about 12mm) for a range of vertical effective stresses and shear speeds.

Bolton et al. (2007, 2009) observed that an ultimate drained friction factor μ^* (soil-soil shear strength divided by normal stress) of 0.6 was typical for West African clays.

By accepting this value for μ^*, the following observations are made for Figure 3:

- The apparent preconsolidation stress σ'^*_c may range from 6kPa to 35kPa for the samples tested.
- An arithmetic mean of approximately $\sigma'^*_{c,mean}$ = 16kPa is suggested.
- No rate-dependant trends can be inferred from the current data.

The variation in σ'^*_c may be due to the presence of randomly distributed groups of pellets within the sample.

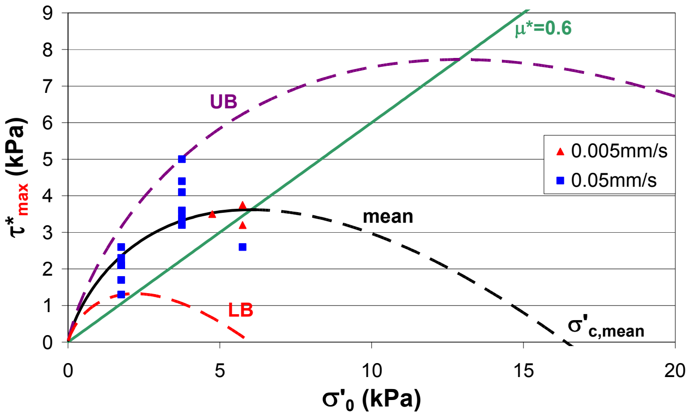


Figure 3. Soil-soil peak strengths for variable shear speeds.

Figure 4 presents the results of maximum strength values for interface shear tests undertaken on samples for a range of shear speeds. Two coating roughnesses were used: 'smooth' (5µm) and 'rough' (95µm).

An adhesion factor α (shear strength observed for interface sliding divided by maximum shear strength) was assumed to be 0.8 following Bolton et al. (2007) resulting in $\mu = 0.8\mu^* = 0.48$. The following observations are made for Figure 4:

- $\sigma'_c \approx 0.8\sigma'_{c,mean}$ is found to define a reasonable upper bound Cam-clay surface for τ_{max}.
- A surprising lower bound of zero is found for rough interfaces.
- Somewhat counter-intuitively, shearing on the smooth interface produces larger strengths than rough interfaces.
- Shear rate does not have a significant influence on τ_{max}.

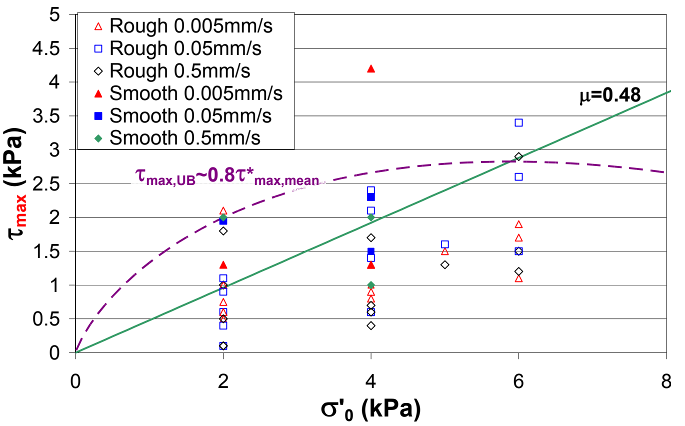


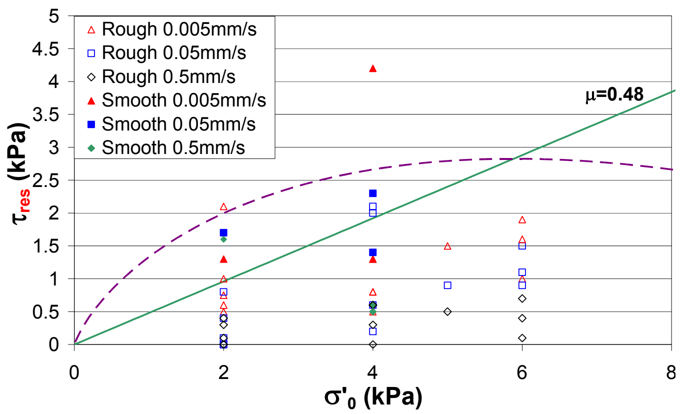
Figure 4. Interface peak shear strength results for smooth and rough coatings and variable shear speeds.

Figure 5 presents residual strength values, τ_{res} for the corresponding τ_{max} values in Figure 4. Residual strength was measured after shearing the samples for a distance of approximately 50mm, at which point the sample at the soil-coating interface should be in a remoulded state.

Observations made from Figure 5 are:

- Residual strengths τ_{res} on a rough interface may be as small as zero at vertical effective stresses within the range tested.
- Residual strengths for a smooth interface approximate peak strengths τ_{max}.
- Shear rate appears to influence τ_{res} only for larger vertical effective stresses.

Figure 5. Interface residual shear strength results for smooth



and rough coatings and variable shear speeds.

3.2 *Oedometer test results*

Figure 6 shows the results of two oedometer tests undertaken on undisturbed samples from 0.25m and 0.3m depth. These samples were subject to staged loading taking the vertical effective stress to greater than 10kPa, approximating the in situ overburden stress at 3m depth. For comparison, results obtained by De Gennaro et al. (2005) from an oedometer test on a sample at 4m depth are shown. A normal compression line determined by De Gennaro, et al. (2005) is also shown. A precompression vertical effective stress of approximately 1kPa is found for the tested samples.

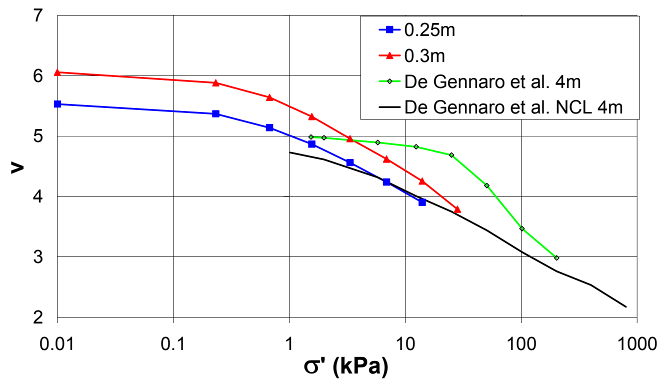


Figure 6. Oedometer test results for sample depths of 0.25m and 0.3m with comparison with De Gennaro et al. (2005).

Figure 7 shows typical photographs of samples taken pre- and post-compression. Whereas the largest pellets have been crushed, the post-compression photograph still displays a 'granular' appearance.

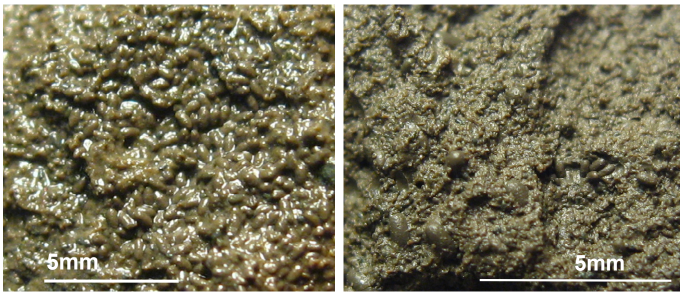


Figure 7. Comparison of sample fabric pre- (left) and post- (right) oedometer testing

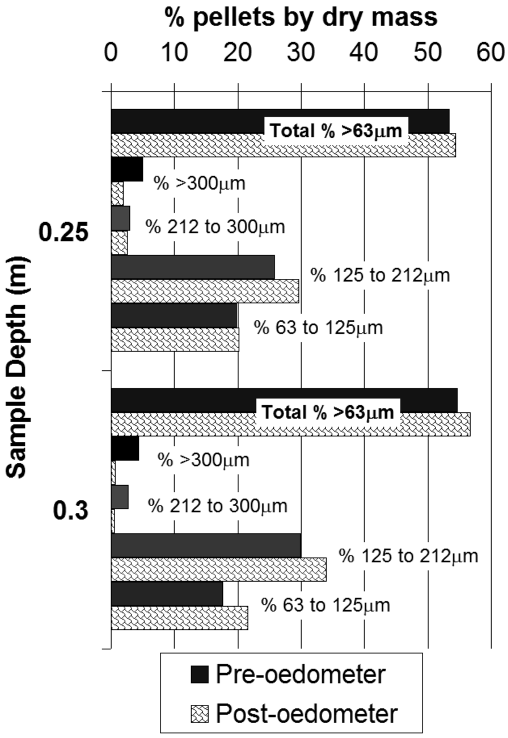


Figure 8. Variation in percentage of pellet sizes prior and post oedometer testing.

Wet sieving was undertaken of trimmings before testing and samples after testing to determine the percentage of pellets: Figure 8. The following points are made:

- Prior to testing, a significant proportion (>50%) of the material comprises pellets;
- The proportion of pellets after testing was not significantly different; and,
- Larger pellets may be crushed resulting in a greater number of smaller fragments.

3.3 *CT imaging and ESEM for internal structure*

Figures 9 and 10 show the presence of voids at different scales within undisturbed samples and washed samples of pellets. Water-filled macro-voids (0.1mm to > 1mm size; Figure 9) are found adjacent to pellets and micro-voids (<1µm to 3µm size; Figure 10) are observed within the pellets. ESEM imaging with the variable pressure secondary electron (VPSE) detector allows the identification of 'wet textures' including some evidence for mucin membranes surrounding pellets. By imaging with a back scatter detector in a wet chamber, information about the structure of pellets can be resolved, showing the arrangement of clay platelets at the surface of pellets.

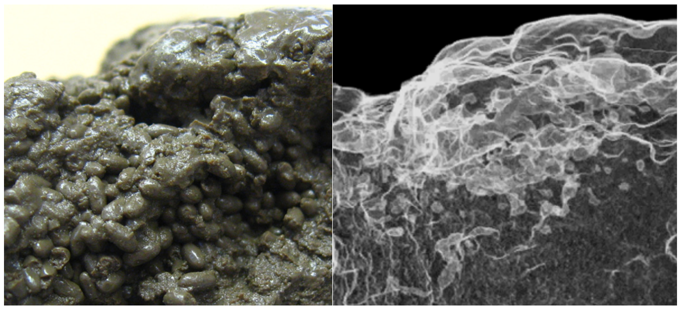


Figure 9. Photograph (left) and X-ray (right) of undisturbed sample showing pellets (~1.5mm diameter) and macro voids.

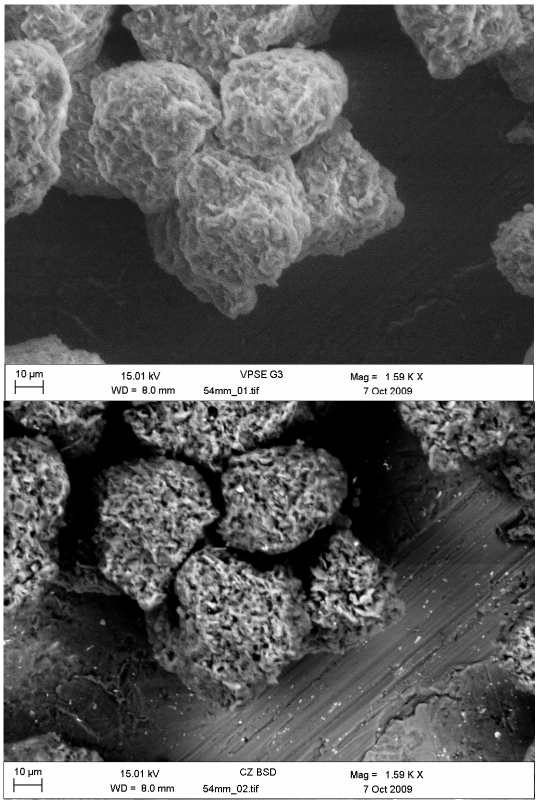


Figure 10. ESEM of pellet aggregates > 50µm showing micro-voids: VPSE (top), back scatter SE detectors (bottom).

3.4 *Discussion of key observations*

Faecal pellets are described by zoologists as being "compacted" (overconsolidated or desiccated in geotechnical terms) and bound with mucous within the gut of their depositors. Their inherent robustness is demonstrated by survival during one-dimensional compression and the wet sieving process.

Cam-shear test results shown in Figures 3 to 5 demonstrate the variability in shear strength that is obtained from testing undisturbed samples. This variability is attributed to the random distribution of faecal pellets found at the sheared surface. Observed macro-voids between pellets provide a source of pore water. Shearing against a rough interface may disintegrate pellets, thereby temporarily reducing intergranular stresses and increasing pore pressures until excess water can escape. In the mean time, “hydroplaning” can occur on the trapped water film, eliminating interface friction. The abundance of faecal pellets may therefore be used to explain the shear behaviour seen in Figures 4 and 5. Even slow shearing at 0.005mm/s does not guarantee that the peak strength will be fully drained. The pore pressures caused by pellet crushing are slow to dissipate, even though extensive open burrow networks are observed in core samples (Kuo and Bolton, 2009b).

Oedometer tests show that elements of pelletised structure remain even at vertical effective stresses exceeding the overburden stress at the base of the crust. Pellet percentages at sediment depths greater than 1m, however, do decrease to 20% for pellets larger than 63μm (Kuo and Bolton, 2009b). If increase in stress is not the cause, other factors such as a continuation of biological activity at greater depth may be responsible for the gradual destructuring of pellets. Given that the sedimentation process in these water depths may be at least three orders of magnitude slower than the bioturbation processes that may initially produce the crust, it is also feasible to suggest over the same time-frame but at a greater depth, a different species of invertebrates are working to remove the crust. Removal of the crust may be manifested through reworking of larger pellets into smaller agglomerates or complete destructuring of pellets by removal of mucins that bind pellets together. This may then allow ‘resedimentation’ of material within pellets that were initially overconsolidated.

4 CONCLUSIONS

This paper presents recent Cam-shear testing of undisturbed samples of West African clays from circa 1500m water depth and from 0m to 0.5m soil depth, highlighting the significant variability of shear strengths that may be encountered. Of interest and concern to pipeline designers is the potential for extremely low friction values approximating zero when samples are sheared on a rough pipeline coating. These values are, however, only indicative of monotonic shearing over a limited distance. Friction values for intact cores undergoing cyclic pipeline movements have not yet been investigated. Based on CT, ESEM, optical imaging, and wet sieving, it is shown that over 50% of the undisturbed samples are in the structured form of robust faecal pellets, the proportion which is sufficiently high to influence the mechanical behaviour of these sediments. These pellets are therefore suggested to be the origin both of high crust strength and the significant variability of both peak and residual interface friction. It is hypothesised that a continuation of biological activity at greater depth may be a major contributing factor to the crust’s demise.

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