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The relationship between the texture of polypropylene coatings and interface friction for sand at low stress levels

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Abstract

Pipelines in the offshore sector make common use of polypropylene (and other polymer) coating systems to protect the infrastructure and provide thermal insulation. High Pressure High Temperature (HPHT) pipelines are subject to large axial loads due to restraint by seafloor soils of thermal strains in the pipe wall. Friction between pipe coating material and seafloor soil plays a defining role in the build-up of axial stress and the formation of lateral buckling. Accurate quantification of pipe-soil interface friction is key to robust pipeline stability design and possibilities to enhance or manipulate the friction coefficient may be attractive to designers. An extensive campaign of soil and interface tests using a range of granular materials and polypropylene surface specimens engineered to achieve varying surface textures was carried out. The results show that interface friction primarily depends on stress level and the magnitude of the surface texture in relation to the particle size. Herein, a new relative textural parameter, T_a , is developed that, unlike alternative relative roughness parameters, can be obtained using conventional profilometry measurement techniques. An expression for estimating the friction factor in relation to texture and stress level is proposed which can serve as a useful predictor of pipe-soil interface friction.

Keywords

Interface Friction; Laboratory tests; Pipes & pipelines, direct shear, polymer, sand

1. Introduction

Offshore pipelines undergo significant changes in effective axial stress between their as-laid condition and their operational state caused by variations in pipe temperature and internal pressure, typically in the order 100°C and 10,000 kPa or more (Hobbs 1981). Expansion of the pipe, where resisted by the soil, generates an axial stress that is relieved by the formation of buckles triggered when a critical threshold is reached. The critical threshold for buckling, known also as initial lateral breakout resistance, the lateral residual resistance, and the magnitude of axial stress build-up are governed by pipe-soil interaction (PSI). The interface friction component of PSI (either axial or lateral) can be typically expressed by a friction coefficient, μ , determining the shear resistance as a fraction of the applied normal stress. Where the friction coefficient is very low, the rate of axial stress build-up is lower but large end expansions of the pipe can occur, which may be undesirable. Conversely, if the pipe becomes sufficiently constrained that strain cannot be accommodated axially, then buckling may occur – the magnitude and spatial distribution of which is influenced by lateral soil confinement along the buckle and axial soil resistance in the buckle feed-in zone. Proper quantification of pipe-soil interface friction coefficient along the pipeline is an important exercise. Pipe-soil interface friction often has conflicting implications for different limit states so being able to engineer and specify the friction coefficient is an attractive possibility.

Polypropylene coating systems are widely used in offshore applications, including pipelines where they protect the steel pipe from corrosion or transport and provide thermal insulation to prevent phase separation inside. Considerable research has been directed to assessment and quantification of interface strengths of granular soils and steel, typically related to piles and for concrete-soil interfaces. Such stiff surfaces are well characterised but there is a paucity of information available with respect to softer (but still stiff) forms of polymers in these applications. Most information available for polymers or soft interfaces is for their flexible form, i.e. geomembranes and geotextiles, which are not directly applicable to pipeline coatings. Considerable energy in the literature has also been directed at the behaviour of pipelines on clay soils including laboratory (e.g. Boukpeti and White 2017; Westgate et al. 2018), theoretical (e.g. Bruton et al. 2007; Cheuk et al. 2008), numerical (e.g. Wang et al. 2010; Ansari et al. 2014), scale model (e.g. Cheuk et al. 2006; Dingle et al. 2008), and full-scale or field survey (e.g. Schaminee

et al. 1990; White and Cathie 2011) investigations. However, with a few exceptions (e.g. De Leeuw et al. 2021), there is little information on the interface behaviour between polypropylene coatings and granular soils at a level applicable to pipeline and offshore engineers. Concrete- and steel-soil interface strengths are traditionally considered to be controlled by the surface roughness (Uesugi and Kishida 1986a; Jardine et al. 1993; Porcino et al. 2003; Lings and Dietz 2005; Dietz and Lings 2006; Han et al. 2018), whereas work into polymers has been focussed on a limited range of parameters disregarding roughness and concentrating instead on surface hardness (O'Rourke et al. 1990).

Numerous researchers have investigated interface behaviour for a range of other polymers (e.g., Saxena and Wong 1984; Negussey et al. 1989; O'Rourke et al. 1990; Dove and Frost 1999; and many more), with the majority concentrated on application to geomembranes and geotextiles which are rather different in nature to the more rigid form used in the application of pipeline coatings. Unique relationships have been revealed between surface texture relative to grain size and interface response (both strength and dilatancy) for sands with wide-ranging particle sizes and surfaces - much harder than those investigated here (Lings and Dietz 2005; Dietz and Lings 2006). No such relationship has been developed for softer polymer surfaces like polypropylene and hardness is known to influence interface strength as O'Rourke et al. (1990) showed in their study of various polymer pipeline coatings.

A series of sand-polypropylene direct shear interface tests were conducted using four sands of varying D_{50} : three commonly available test sands and one dredged. Counterpart sand-only direct shear tests were also carried out to provide a benchmark for comparison. To reproduce pertinent seabed conditions for offshore pipes, the tests were carried out water-saturated in a surface-over-soil configuration using a specially adapted interface load pad, and at stress levels of between approximately 2 kPa and 25 kPa that are relevant to offshore pipelines (White and Cathie 2011). Polypropylene test specimens were acquired variously from pipeline coatings manufacturers, or material stock merchants. The experimental campaign sought to test the interface shear characteristics of specimens extracted from samples of coating removed from real pipes and develop a relationship to allow polymer interface friction to be predicted given a stress level and surface texture. To do this it is necessary to test across a wide range of surface textures. Five varieties of surface specimens were used, namely (1) samples of coating extracted from

subsea pipes, samples from polypropylene sheet textured by (2) laser engraving and (3) subsequently sandblasted, (4) samples of pipeline coating indented using a knurled steel plate under a hydraulic press, and (5) virgin polypropylene sheet to provide a highly smooth example. Based on experimental results, an expression for estimating the friction factor in relation to texture and the stress levels expected in superficial pipelines will be proposed.

2. Materials

2.1 Test soils

The test soils have been selected to cover the range in grading of typical North Sea sediments. The typical range of particle size distributions for granular soil types is indicated by the grey shadow in Figure 1 along with particle size distributions for the test soils chosen for this study. The selected test soils are three industrial sands known in the literature: Leighton Buzzard 14-25 (also known as Fraction B), Hostun Sand, and Redhill Sand. The coarsest test soil is called Lowestoft Gravel and consists a mixture of material dredged from the North Sea, east of Lowestoft, and approximately 30% (by mass) crushed quartz-rich aggregate. Index characteristics are provided in Table 1. In general, the Lowestoft Gravel and the Hostun Sand grains are subangular to angular (as after Norbury 2010). Hostun Sand grains have medium to high sphericity whereas Lowestoft Gravel grains vary in shape from elongate and tabular to more spherical. Leighton Buzzard and Redhill sand grains are generally subangular to subrounded and are both medium to high sphericity.

Figure 1 (a) Particle size distribution of the four sands and the envelope (grey zone) within which typical North Sea granular sediments sit (Milewski, et al. 2019) though usually within a fairly narrow band.

Table 1 Index characteristics of the test soils

	Lowestoft Gravel	Leighton Buzzard	Hostun Sand	Redhill Sand
$\rho_{\max}$ (Mg/m ³)	1.71	1.73	1.64	1.65
$\rho_{\min}$ (Mg/m ³)	1.37	1.44	1.33	1.30
$e_{\max}$	0.94	0.84	1.00	1.04
$e_{\min}$	0.55	0.53	0.62	0.61
D_{50} (mm)	1.59	0.88	0.35	0.17
$C_u = D_{60} / D_{10}$	1.88	1.44	1.71	2.22
$C_c = D_{30}^2 / (D_{10} D_{60})$	1.00	0.99	0.90	1.17

2.2 Polypropylene surfaces and preparation

The five types of polypropylene surface specimens are described in the following.

Type “V” surfaces: Virgin polypropylene specimens

To provide a repeatable set of specimens for subsequent modification and to get surfaces with as practically close to pristine as possible, commercially available polypropylene sheet was used. It had a Shore D hardness of approximately 75 at ambient laboratory temperatures of between 20° and 22°C, which is very similar to the pipe coating specimens used in this work.

Type “T” surfaces: Polypropylene pipe coating specimens

Test specimens with prototype characteristics were obtained by stripping polypropylene coated pipeline segments of their coating, flattening the removed material under load at elevated temperatures, and cutting to size. These specimens are from the same batch as previously tested and described in De Leeuw et al. (2021). Specimen hardness was approximately 70 on the Shore D scale at ambient laboratory temperatures of between 20° and 22°C.

Type “E” and “S” surfaces: Enhanced roughness polypropylene specimens

Specimens tested with enhanced surface textures were obtained in sheet form from a material stock merchant, as previously described, and cut to size in the laboratory. Two methods of enhancing the surface texture were employed: laser engraving and laser engraving followed by sandblasting with Leighton Buzzard sand. The laser engraved pattern consisted rows of 2 mm circles directly abutting one another and offset by half a diameter from row to row. A schematic of the arrangement is shown in Figure 2. Instead of ablating the material, as would be typical for a laser-engraver, melt zones were created which cooled to form a new textured surface.

Figure 2 Schematic diagram of the laser engraved pattern.

Sandblasting already engraved surfaces (hereafter referred to only as “sandblasted”) preserved the underlying surface morphology but superimposed a sharper, rougher texture. Typical examples of 2D surface profiles (determined by the procedure described later in section 2.3) from each surface type are presented in Figure 3. It appears that sandblasting the surface has not only increased the profile amplitude, but also reduced the effective wavelength.

Figure 3 Schematic representation of typical surface profile from each surface type. For reference, the mean particle size in mm for each soil is LG = 1.59, LB = 0.88, HS = 0.35, and RH = 0.17.

Type "P" surfaces: Pressed polypropylene pipe coating specimens

Specimens for pressing were obtained from an industrial pipeline coatings manufacturer and prepared in the laboratory. Sections of coating were initially cut to size and then flattened under 20 kg masses at approximately 160°C to remove any curvature. A steel plate of similar dimensions to the surface specimens was fabricated with a knurled surface comprising tetrahedral protrusions 3 mm in height with slope angles of 45°. The knurled steel plate and surface specimens were heated to approximately 180°C to soften the polypropylene to the brink of melting; Shore D hardness was reduced from approximately 70 to between zero and five. When sufficiently softened, surface specimens were sandwiched between the two heated steel plates, one smooth to act as a base and the knurled plate on top, and the two pressed together using a manually operated hydraulic jack. The knurled surface of the steel plate is represented schematically in Figure 4.

Figure 4 Schematic representation of a section of the knurled surface used to impress the polypropylene specimens.

2.3 Surface texture

Texture of surface specimens was quantified prior to testing using an Alicona Infinite Focus which uses a microscope and focus-variation to optically map 3D surfaces. The benefits of the Alicona non-contact profilometry over more conventional contact-profilometry is that damage to the surface during measurement is avoided. Milewski et al. (2019) showed that on softer surfaces such as polypropylene, non-contact methods are preferable as diamond-tipped stylus techniques can suppress measured roughness by up to half by physically ploughing through asperities. The Alicona uses a microscope to scan a 3D surface using focus variation to generate a surface of ordinates in X, Y, and Z. From the generated scan, 2D profiles can be drawn from which the in-built software determines parameters of interest. Due to unavailability of equipment, the more conventional method of contact profilometry using a Taylor Hobson Form 50 Talysurf was employed for the “V” specimens. However, in spite of the draw back previously described, the “V” specimens are relatively insensitive to this problem as even doubling the result as after Milewski et al. (2019) would have a negligible effect.

There is considerable precedent in the literature for the use of roughness parameters to describe interface surface texture but texture also comprises longer wavelength features referred to as waviness and form. The surface texture parameters (form, waviness, and roughness) are distinguished only by their wavelength which varies according to application (Raja et al. 2002). It is clear from Figure 3 and from the surface structure of Figure 4 that when considering the x-axis scale, the range of D_{50} of the test soils (0.17 to 1.59 mm) that both the roughness and waviness are likely to have controlling effects on soil-surface interaction. Therefore, these distinctions are disregarded and instead surfaces are considered only in terms of their overall texture, T , to avoid confusion with existing terms. Surface parameters have a variety of metrics but two often used are the arithmetic mean average of absolute deviations from the centre line, T_a , or the maximum absolute deviation, T_{max} , analogous to Jardine et al. (1993) and Uesugi and Kishida (1986b) respectively. De Leeuw et al. (2021) showed that for pipeline coating materials where there may be manufacturing artefacts substantially larger than the representative surface texture, average values are the more appropriate metric so T_a is adopted in this work. Profilometry techniques make use of cut-off filters (L_c) to remove large wavelength information (i.e. remove wavelength information larger than L_c) from a profile to focus on surface texture at a scale applicable to the

phenomenon of study - in this case, interface soil-surface shearing. Figure 5 shows the variation of T_a with different L_c cut-off lengths for each surface type. Although measured T_a varies, there is a clear distinction between the five surface types and overall distinctions in texture are clear.

Figure 5 Change in R_a with long wavelength cut-off filter, L_c

It is well recognised that the effective texture of an interface surface is affected by particle size of the interface soil and as such is commonly quantified using a measure of relative parameters as in Uesugi and Kishida (1986b). Such parameters recognise that the degree of engagement or meshing between a granular material and a surface, and hence the shear resistance offered, is dependent on the relative size of particles in relation to the magnitude of the surface texture. A given surface appears to have a greater magnitude of texture to a finer grained soil. Relative parameters quantify the degree of meshing by expressing the surface texture as a proportion of mean particle diameter giving the parameter of interest. Relative texture is defined:

$$T_{\text{relative}} = T_a / D_{50} \quad (1)$$

In addition to normalising texture by the grain size it is also necessary to consider the scale over which it is measured. Uesugi and Kishida (1986b) limited their scope to roughness and measured over a length equal to D_{50} so that large asperities that a longer profile might have picked up would not be counted as it would not have affected the particles in question. Surfaces considered in this research have a much wider bandwidth, including features traditionally referred to as roughness, waviness, and form, so Uesugi and Kishida's (1986b) philosophy is applied to surface texture as previously defined. It is necessary to consider the surface texture at the appropriate wavelength,

an effect Uesugi and Kishida (1986b) achieved by measuring their surface over a length equal to D_{50} . In the current work the same effect is more easily achieved by manipulation of the cut-off filter, L_c . Figure 5 shows that as the magnitude of the (high-pass) filter, L_c , decreases, progressively more long-wavelength information is removed from the surface profile resulting in lower measured texture. Having previously defined the relationship for relative texture, setting $L_c = D_{50}$ achieves the same as Uesugi and Kishida (1986b) intended and reveals the appropriate T_a for any test sand in question for a given surface. Table 2 summarises the appropriate relative texture for each sand-surface combination.

Table 2 Summary of relative texture ($T_{relative}$) for each sand-surface interface

Soil	“V”	“T”	“E”	“S”	“P”
Lowestoft Gravel	$3.0 \cdot 10^{-5}$	$5.6 \cdot 10^{-4}$	$4.1 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
Leighton Buzzard	$4.9 \cdot 10^{-5}$	$9.7 \cdot 10^{-4}$	$3.3 \cdot 10^{-3}$	$1.6 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
Hostun Sand	$1.0 \cdot 10^{-4}$	$2.3 \cdot 10^{-3}$	$5.1 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$
Redhill Sand	$1.7 \cdot 10^{-4}$	$5.1 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$	$2.0 \cdot 10^{-2}$	$2.5 \cdot 10^{-2}$

3. Testing Apparatus

The Direct Shear Apparatus (DSA) used in this work has been modified to improve the articulation of the force transmission system so that the loads acting on the included soil specimen are more reliably quantified. Full details of the modified apparatus, called the Winged Direct Shear Apparatus (WDSA), are in Lings and Dietz (2004) and its benefits for the current application of testing at very low stresses are discussed in De Leeuw et al. (2021). The WDSA accommodates a 100 mm by 100 mm shearbox instrumented with four Linear Variable Differential Transformers (LVDTs) to measure horizontal and vertical displacement and top cap rotation, and an S-Type 500 Newton load cell. Figure 6 shows the schematic arrangement of the WDSA including placement of instrumentation.

Figure 6 Schematic drawing of the WDSA test apparatus

For interface tests the upper half of the shearbox was replaced with an aluminium load pad to which the surface specimen could be secured. Interface tests were carried out in a surface-over-soil configuration to more closely resemble conditions of a pipe laid directly on the seafloor (pipe curvature notwithstanding). De Leeuw et al. (2021) show that with careful sample preparation the typical drawback of surface-over-soil testing - pre-shearing of the soil sample at interface - can be avoided. In reality, installation of a pipe on the seabed will cause pre-shearing so an undisturbed initial state is a luxury of laboratory test conditions. All tests were carried out saturated with the shear carriage gently flooded with water at ambient laboratory temperature (between 20 and 22°C) prior to application of the normal load.

4. Sample Fabrication

4.1 Soil tests

Direct shear soil test samples were prepared with a pre-installed gap of $5 \cdot D_{50}$ between the upper and lower shearbox halves. Dietz and Lings (2004) demonstrated empirically that setting such a gap size resulted in no change, or drift, in the measured large-displacement shear strength during direct shear testing, indicating that the ever-reducing soil-soil plan area within the shearbox was not impacting the ultimate shear strength. Rubber edging was placed around the inside of the shearbox to shield the gap and prevent sample loss, with a split in the edging at the midpoint of the shear zone to allow for shear to occur unimpeded. Lings and Dietz (2004) carried out a

parametric study on the use of rubber edging in their development of the Winged Direct Shear Apparatus used in this work and did not find it compromised results. The use of such edging follows earlier works by Al-Douri and Poulos (1992) and Shibuya et al. (1997). Al-Douri and Poulos (1992) noted a negligible (in fact, unmeasurable) effect of the edging during testing.

Following the advice of Miura et al. (1997) for achieving the highest possible void ratio, soil was poured through a funnel, ensuring zero drop height between funnel tip and the top of the soil pile, to form a conical heap. The soil was gently spread and levelled before an aluminium plate was placed over it and vibrated to densify the sample to the desired density. The top plate was secured inside the upper shearbox frame to obtain the symmetrical test arrangement recommended by Jewell and Wroth (1987).

4.2 Interface tests

Similar to soil tests, a thin rubber skirt was placed inside the box to screen the edges and cover a pre-installed gap of 4 mm between the shearbox halves. Samples were prepared upside down (i.e., soil was poured onto the surface that would later form the top half of the interface test in a surface-over-sand configuration) and followed the same deposition procedure as soil-only shearbox tests. The bottom of the shearbox was sealed with a large aluminium base plate fully covering the bottom of the frame and then the whole box was smoothly but decisively inverted to the correct test orientation and placed inside the shear carriage. The procedure, and rationale, is discussed in more detail and the interface load pad more fully described in De Leeuw et al. (2021).

5. Testing programme

A total number of 32 direct shear soil tests and 128 interface tests were conducted: 16 on virgin polypropylene sheet, 32 on coating specimens, 32 on engraved specimens, 32 on sandblasted specimens, and 16 on pressed specimens. The complete data and cardinal parameters for all tests in this work are available in De Leeuw (2020). The ultimate shear stress, τ_{ult} , is taken as the average shear stress between 10 mm and 12 mm of horizontal displacement (with rare exceptions where the test ended early), while the peak shear stress, τ_{peak} , is the maximum shear stress recorded during the test. The void ratio of the samples after consolidation by application of the normal load is indicated by e_{con} . For each soil, two target nominal relative densities were prepared

(D_r approximately 15% and 70%) at four levels of vertical confining stress, σ_n (approximately 2, 5, 10 or 15, 20 kPa). A three-part test naming convention has been adopted to uniquely identify each test starting a soil-type reference [LG, LB, HS, RH], followed by a density reference [L (for loose), D (for dense)], and a confining stress level reference [2, 5, 10 or 15, 20 kPa]. The horizontal displacement rate was approximately 0.8 mm/minute.

For pipe coating “T” specimen interface tests a single surface specimen was used for each series of tests with the same test sand. Testing was conducted in order of increasing confining stress to minimise the impact of any surface damage caused during shearing, and loose before dense (where applicable). Virgin, engraved, and sandblasted interface tests used a fresh surface specimen for every test. Pressed interface tests used a single surface specimen for every test. Like the soil-only tests, the horizontal displacement rate was approximately 0.8 mm/minute. For interface tests the test reference includes a surface type reference at the end [V (for virgin sheet), T (for coating specimens), E (for laser engraved), S (for sandblasted), P (for pressed)].

6. Results and discussion

6.1 Soil strength

Soil tests exhibited classical stress-dilatancy typical of granular materials. Loose sample tests mobilised only ultimate shear strengths accompanied by sample contraction. Dense sample tests dilated and exhibited peak-post peak behaviour. Figure 7 presents failure envelopes for each test sand in the ultimate state for loose and dense samples and the peak state for dense sample tests. Failure envelopes are presented in terms of stress ratio (τ_{ult}/σ_n) for clarity with friction angles, ϕ , detailed in Table 3. Friction angles were determined from a best fit through shear stress plotted against normal stress with the line forced through the origin. All soil tests show good agreement between the loose and dense ultimate strengths, as expected. Failure envelopes are generally slightly nonlinear and exhibit greater mobilised strengths with lower confining stress, consistent with the expected behaviour of dry cohesionless soils (Bolton 1986; Sture et al. 1998; Fannin et al. 2005; Chakraborty and Salgado 2010).

Under very similar conditions and with the same apparatus as the present work, Lings and Dietz (2004) measured ultimate shear strengths for Leighton Buzzard as on average 30.2° and 30.5° at within 5% of the density of the dense and loose conditions in the present study,

respectively. The ultimate strengths also compare well with the 32° friction angle found by Mandolini et al. (2019) under pure shear loading in the hollow cylinder torsional apparatus.

Figure 7 Failure envelopes presented as shear stress ratio (τ/σ_n) and confining stress for (a) Lowestoft Gravel, (b) Leighton Buzzard, (c) Hostun Sand, and (d) Redhill Sand.

6.2 Interface strength

Figure 8 presents interface shear responses for Leighton Buzzard across each surface specimen type and Figure 9 presents the interface shear responses for each test sand across two surface specimen types for dense samples only. These two figures together show the range of typical behaviours across the data set. Virgin sheet (“V”) and pipe coating (“T”) surfaces have an elastic-perfectly plastic type shear response where shear stress rapidly reaches a maximum within 0.5 mm of horizontal displacement beyond which shear stress remains relatively stable. There is little appreciable difference in shear response between loose and dense sample tests for these surfaces other than a tendency for loose sample tests to consolidate slightly more during testing

and for dense sample tests to mobilise a slightly greater shear stress. Overall, vertical displacements are negligible, which is consistent with previous findings in De Leeuw et al. (2021) suggestive of grain sliding dominating shearing behaviour across smooth surfaces (O'Rourke et al. 1990). There is a similar trend for engraved ("E") surface specimens to behave quasi elastic-perfectly plastically. There is no clear peak-postpeak behaviour in dense sample tests although the initial increase in shear stress to its maximum is more pronounced than in the loose sample test. There is significantly more sample contraction in the loose sample tests than dense sample tests, which is not unexpected. Limited vertical displacement and lack of obvious peak-postpeak stress-dilatancy suggests that grain sliding still dominates shearing behaviour. In contrast, the sandblasted ("S") surface results exhibit classical stress-dilatancy with clear peak-postpeak behaviour. Vertical displacement in both loose and dense sample tests are consistent with stress-dilatancy which suggests the shearing mode has evolved from predominantly grain sliding to more grain rolling and the surface texture playing the part of neighbouring soil grains from the saw-tooth model of soil grain packing. Similar behaviour is seen for pressed ("P") surface specimens.

Figure 8 Interface shear response plots for Leighton Buzzard across the five surface specimen types.

Figure 9 Interface shear response plots for each test sand across “T” and “S” surfaces in dense condition.

6.3 Interface test strength envelopes

The range of strength envelopes across each surface type is captured in Figure 10 and across each sand type in Figure 11. Angles of interface friction for each soil and surface type combination are summarised in Table 3. The increase in strength from pristinely smooth virgin polypropylene to the engraved, sandblasted, and then pressed specimens follows the expected pattern given their enhanced surface texture. Interface angles of friction for virgin sheet and pressed specimen loose tests are not available due to such large vertical settlement that the surface came into contact with the lower frame compromising the integrity of the results.

Figure 10 Failure envelopes in terms of shear to normal stress ratio for Leighton Buzzard across each test soil.

(a) Loose ultimate "T" and "S"

(b) Dense peak "T" and "S"

(c) Dense ultimate "T" and "S"

-▲- LG (S) -●- LBB (S) -■- HS (S) -◆- RH (S)
 -◆- RH (T) -●- LBB (T) -▲- LG (T) -■- HS (T)

Figure 11 Failure envelopes in terms of shear to normal stress ratio for and for each soil type with "T" and "S" surfaces.

Table 3 Summary of soil and interface angles of friction

Interface	Loose ultimate	Dense peak	Dense ultimate
Soil strength			
Lowestoft Gravel	32.6	40.5	32.8
Leighton Buzzard	30.7	40.0	30.5
Hostun Sand	33.0	41.5	31.3
Redhill Sand	32.2	39.9	33.3
Virgin sheet (V)			
Lowestoft Gravel	-	11.9	10.8
Leighton Buzzard	-	11.9	9.4
Hostun Sand	-	21.5	19.9
Redhill Sand	-	14.2	14.1
Coating (T)			
Lowestoft Gravel	11.3	13.4	11.2
Leighton Buzzard	9.4	10.5	8.4
Hostun Sand	18.4	21.6	20.0
Redhill Sand	17.3	19.2	18.4
Engraved (E)			
Lowestoft Gravel	19.0	21.1	17.6
Leighton Buzzard	16.4	20.4	19.3
Hostun Sand	22.1	27.0	26.0
Redhill Sand	18.4	23.6	23.3
Sandblasted (S)			
Lowestoft Gravel	28.6	33.7	28.8
Leighton Buzzard	28.4	36.9	29.2
Hostun Sand	29.6	36.4	31.6
Redhill Sand	25.1	33.7	30.5
Pressed (P)			
Lowestoft Gravel	-	38.4	32.4
Leighton Buzzard	-	38.0	31.7
Hostun Sand	-	37.2	32.1
Redhill Sand	-	34.6	30.9

6.4 Interface dilatancy

In addition to the increase in ultimate strength as the texture is enhanced, there is also an increasing difference between peak and ultimate strengths reported in dense tests. Accompanying the increasing peak strength is the increasing vertical displacement and dilative behaviour. Bolton's (1986) empirically derived flow rule for sand tests can be used to evaluate the relationship between shear stress and dilation:

$$\varphi_{\text{Bolton}} = \varphi_{\text{cs}} + 0.8 \cdot \psi_{\text{peak}} \quad (2)$$

According to this expression, the peak friction angle (ϕ_{Bolton}) is equal to the critical state friction angle (ϕ_{cs}) plus peak angle of dilatancy (ψ_p) modified by a coefficient, $K = 0.8$, where dilatancy is taken as the maximum slope of the vertical displacement plot corresponding to peak shear stress. Assuming the phenomenon of interface dilatancy abides by equivalent laws, this expression can be rewritten:

$$\delta_{\text{Bolton}} = \delta_{\text{ult}} + K \cdot \zeta_{\text{peak}} \quad (3)$$

Relevant parameters can be evaluated from the experimental data as follows:

$$\tan \delta_{\text{peak}} = \tau_{\text{peak}} / \sigma_n \quad (4a)$$

$$\tan \delta_{\text{ult}} = \tau_{\text{ult}} / \sigma_n \quad (4b)$$

$$\tan \zeta_{\text{peak}} = (\Delta_z / \Delta_x)_{\text{max}} \quad (4c)$$

in which δ_{peak} is the peak angle of interface friction, δ_{ult} is the ultimate angle of interface friction, ζ_{peak} is the maximum angle of interface dilatancy, Δ_x is the incremental shear displacement, and Δ_z is the incremental vertical displacement. The comparison between the experimental measurements for engraved, sandblasted, and pressed surface specimens and Bolton's reworked expression is presented in Figure 12a where a perfect agreement would manifest as a 1:1 relation (indicated by the dashed straight line).

Figure 12 (a) Measured δ_{peak} compared to $\delta_{\text{Bolton}} = \delta_{\text{ult}} + K \zeta_{\text{peak}}$ and (b) peak interface friction angle and interface dilatancy. Only results for “E”, “S”, and “P” surfaces are included.

The grey data points follow Bolton's expression using his original dilatancy coefficient of 0.8. At lower δ_{peak} there is good agreement because dilation is negligible, but when dilation starts to play a greater role a clear divergence develops. Using coefficient $\kappa = 0.55$ brings the data much closer to the idealised 1:1 line which suggests that for the present data the contribution of dilatancy to the peak polypropylene interface strength is less than suggested by Bolton (1986) for sand only strength. However, Bolton's (1986) tests were at 300 kPa and Jewell (1989) observed that the relationship between ultimate and peak strengths with respect to dilatancy becomes less reliable at low stress as is the case here. In addition, there is little lateral confinement due to the preinstalled frame gap. That soil did not spill out of the shearbox suggests soil arching may be occurring which means that the real peak shear stress could be greater than determined assuming the full plan area of the shearbox.

An alternative flow rule for interfaces was determined by Lings and Dietz (2005) who found that for steel-sand interfaces the peak interface friction angle could be well approximated by the equation:

$$\delta_{\text{ss}} = 25^\circ + \zeta_{\text{peak}} \quad (5)$$

Figure 12b presents the peak shear strength of dilatant interfaces tests with their associated peak angle of dilatation. Although there is considerable scatter which means any conclusion from them should be treated with some caution, a linear best-fit through the data gives an intercept of 24° , showing reasonable agreement for the onset of dilation with the interface flow rule of Lings and Dietz (2005) although the slopes are different. Compared with steel interfaces, polypropylene interface strength is above that expected given the mobilised dilatancy. The enhanced polypropylene strengths may be a result of a different weighting of particle-surface interaction mechanisms such as an increase in the propensity for indentation and ploughing (Shooter and Tabor 1952; Dove and Frost 1999).

6.5 Interface efficiency

Interface efficiency is defined as the ratio between interface shear strength and the equivalent soil-only shear strength. Table 4 summarises interface efficiencies for each strength state and details the average interface efficiency of the combined loose and dense ultimate and dense peak states.

Table 4 Summary of interface efficiencies, δ/φ

Surface	Soil (loose ultimate / dense peak / dense ultimate)			
	LG	LB	HS	RH
Virgin sheet	----- / 0.27 / 0.34	----- / 0.35 / 0.63	----- / 0.54 / 0.63	----- / 0.38 / 0.42
Coating	0.36 / 0.34 / 0.38	0.31 / 0.28 / 0.30	0.56 / 0.56 / 0.63	0.55 / 0.47 / 0.53
Engraved	0.57 / 0.53 / 0.63	0.53 / 0.51 / 0.64	0.69 / 0.68 / 0.82	0.59 / 0.62 / 0.70
Sandblasted	0.80 / 0.85 / 0.91	0.92 / 0.92 / 0.96	0.92 / 0.92 / 1.00	0.78 / 0.89 / 0.92
Pressed	----- / 0.97 / 1.03	----- / 0.95 / 1.04	----- / 0.94 / 1.01	----- / 0.91 / 0.93
Average δ/φ				
Virgin sheet	0.30	0.32	0.57	0.40
Coating	0.36	0.30	0.58	0.52
Engraved	0.58	0.56	0.73	0.64
Sandblasted	0.89	0.94	0.94	0.86
Pressed	1.00	1.00	0.98	0.92

Average values from Table 4 are plotted in Figure 13 which shows a generally logarithmic relationship between the relative texture and average interface efficiency. Each sand type shows a similar trend and the solid black line is an averaged approximation showing the general trend across all sand types. As interface efficiency approaches 1, there is a reducing benefit from any additional surface texture. It may be envisaged that as the magnitude of texture increases, the surface texture increasingly meshes with grains sufficiently well to provoke the formation of a shear band in the soil above the surface suggesting that the equivalent soil-only strength imposes an upper limit on interfacial strength. Surfaces that have randomised roughness (analogous to texture) have been shown to be limited in their maximum shear strength to the equivalent internal soil strength (Uesugi and Kishida 1986b; Subba Rao et al. 1998; Dove and Jarrett 2002). Martinez and Frost (2017) note that some highly rough surfaces can generate interface friction greater than the soil internal strength but these types of surface texture are not analogous to the present work so cannot be considered together. The dilatancy zones indicating the type of soil-surface shear response identified by Lings & Dietz (2005) using similar apparatus but using steel surfaces, are indicated for context. The present data follow a similar pattern with an initially smooth zone followed by a transition to fully-rough behaviour. The positions of the transition points are slightly different but this is not unexpected given the very different materials under investigation.

The trends shown in Figure 13 also compare favourably with Dove et al. (2003) though they adopted a stereological approach to characterising roughness so direct comparison is difficult. They measured interface efficiencies in the range of 0.5 to 0.9 for residual strength which

is broadly consistent with the present work; the greater range seen here likely caused by the smoothness of the virgin sheet specimens.

Figure 13 Average (loose and dense ultimate and dense peak) interface efficiency variation with relative texture on natural and logarithmic scales including a general trend line for dilatant surfaces.

6.6 Interface strength and relative texture

Using the relative texture parameters previously discussed can condense interface strength data close to a unique line with respect to roughness which can reveal unique relationships for a given interface. Given the nonlinear nature of strength envelopes the data and trends have been separated out by stress level to give the trends shown in Figure 14. It can be seen from both Figure 13 and Figure 14 that Hostun Sand is an outlier, plotting consistently more strongly than is consistent with the other sands. One explanation is that the sand itself is industrially manufactured by crushing and grinding and therefore is not representative of seafloor sediments, therefore, Hostun Sand is discounted from consideration for determination of a relationship between interface strength and texture. Hostun Sand symbols in Figure 14 are hollow to highlight their omission from derivation of trend lines.

Figure 14 Friction factor (equivalent to the ultimate shear strength, τ/σ_n) and relative texture at 2, 5, and 20 kPa normal stress. Hollow shapes indicate the HS data omitted from curve fitting as discussed in Section 6.6.

Each fitted curve in Figure 14 follows a power law relationship but the coefficients controlling the form of the curve vary subtly between stress levels. The largest difference is in the coefficient controlling the y-axis intercept. The relationship between surface texture and interface friction including stress level considerations is similar to that described by Meyer et al. (2015) but with the omission of strain rate effects as pore pressure generation is not applicable to the sandy soils considered here. Coefficients defining the form of the curves at each stress level (Figure 14) are averaged into a single approximation to give the following expression for the interface friction factor:

$$\mu = a \cdot \left(\frac{T_a}{D_{50}} \right)^b + c \cdot \left(\frac{\sigma_n}{\sigma_f} \right)^d + e \quad (6)$$

Table 5 Coefficients for Equation 6.

Coefficient	Description
T_a	Average texture
D_{50}	Mean average grain size
σ_n	Normal stress
σ_f	1 kPa
a	2.40
b	0.45
c	0.25
d	-0.55
e	0.10

The expression describes the 3D plane shown in Figure 15 with red points representing data used to derive the fit, and blue points are the remaining data included to help show the goodness of the fit. The residual and percentage error between the surface described by the equation and the observed data at approximately 2, 5, and 20 kPa are also included. In general, there is a consistent level of friction coefficient residual error of less than 0.1 across the range of texture. The error is stress level dependent with average error increasing from 4.2, to 7.8, to 11.2% from 2, to 5, to 20 kPa normal stress. The average percentage error across each stress level is 7.7% whilst most of the data fall within 15% error bounds at lower texture and falls within 10% at higher texture. Figure 13 shows that interface efficiency reaches 1 at approximately $T_a/D_{50} = 0.25$ so the plane in Figure 15 is truncated at this value as well. For the types of surfaces tested here the internal soil strength is expected to provide an upper bound to interface strength as previously discussed.

Figure 15 Graphical representation of the friction factor-surface texture relationship varying with applied stress including plots of residuals between the fitted and observed data and error. Red data points on the surface represent data points used to derive the fit.

As previously mentioned, the results for Hostun Sand have been omitted from Figure 15 due to the difference in the nature of the soil, because the results have more scatter, and generally exhibit greater than anticipated strength at low texture (illustrated in Figure 13). However, it is

possible to fit the same expression as defined Figure 15 to the Hostun Sand results with only a minor modification to the “e” term, using instead a value of 0.18. This generates errors of 4.5, 6.1, and 10.8% for 2, 5, and 20 kPa normal stress respectively, with an average of 6.1% which is comparable to the fits for the larger data set.

There are a number of other factors which are known to affect the interface shear response which have not been considered in this research such as soil particle angularity and soil grading. Surface hardness has also not been considered as all the test specimens have a comparable hardness, however, polymer hardness is sensitive to temperature so both the base material and its operating temperature are likely to affect the friction coefficient. Just as modification of the e term allows adequate prediction of the Hostun Sand interface friction with its different material properties, perhaps other factors such as surface hardness and soil grading can be accounted for by an analogous modification.

7. Conclusions

A detailed study of polypropylene coating interface behaviour has been carried out assessing interfacial shear strength, dilatancy, specimen surface roughness and attention given to best determination of roughness. Interface tests were carried out in a surface-over-soil configuration with a Winged Direct Shear Apparatus and using a specially made upper interface load pad. Sample preparation upside down before inverting to the test configuration ensured undisturbed surface-soil contact allowing stress-dilatant behaviour to occur. Four test sands of varying mean grain size were tested with a range of polypropylene surface specimens prepared with different surface roughness characteristics.

Interface strength has been shown to vary according to stress level, density, grain size, and roughness with the latter two variables together allowing the identification of a unique relationship between polypropylene interface strength and relative roughness. Interface stress response varies from non-dilative to fully dilative showing peak and postpeak behaviour with large displacement ultimate strengths analogous to equivalent soil-only shear strength. The onset of dilation brings with it both increasing peak and ultimate strengths and the relationship between ultimate and peak strength follows an adaptation of Bolton's (1986) flow rule. The onset of dilatant behaviour is similar to that of Lings and Dietz's (2005) interface flow rule but the slope is steeper.

Polypropylene surfaces mobilise additional strength that cannot be explain by dilatancy alone and which may be due to an increased propensity for grain ploughing of softer surfaces.

Interface strength of rigid polymer interfaces has traditionally only been considered in terms of surface hardness but this study has shown that surface texture is just as significant as in harder materials like steel. Scope for engineering a surface texture and application in geotechnical engineering may be a useful option in pipeline engineering as it has been shown that up to four-fold increases in strength over unaltered polypropylene are possible. The friction factor is a dominating parameter for stability design of offshore pipelines directly governing the rate of build-up of effective axial stress from constraint of axial strain, breakout resistance, and the nature and size of lateral buckles.

A novel relationship has been identified for the interface shear strength of polypropylene with granular soils according to the surface roughness and stress level which is defined by a simple equation. It is envisaged that the relationship can aid designers in predicting the friction coefficient applicable to pipeline design. The relationship allows for other factors such as surface hardness or grain angularity to be easily accommodated when further data become available.

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