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The Piling in Glauconitic Sand (PIGS) JIP: insights from site characterisation and laboratory testing

*Z. Westgate, D. DeGroot, G. Zhang
University of Massachusetts Amherst, Amherst, Massachusetts, USA

R. Beemer
Virginia Tech, Blacksburg, Virginia, USA (formerly University of Massachusetts Dartmouth, Dartmouth, Massachusetts, USA)

K. Miller, J. Browning
Rutgers, State University of New Jersey, New Brunswick, New Jersey, USA

R. Coffman
University of Arkansas, Fayetteville, Arkansas, USA

A. Senanayake, C. Maldonado
Norwegian Geotechnical Institute, Houston, USA

zwestgate@umass.edu (corresponding author)

ABSTRACT: The Piling in Glauconitic Sand (PIGS) Joint Industry Project (JIP) was established in 2021 to investigate the effects of glauconite on geotechnical behaviour in relation to pile installation and operational performance. This is especially relevant to offshore wind energy development along the U.S. Atlantic Outer Continental Shelf (OCS). The scope of work completed to date comprises (i) characterisation of glauconite / glauconitic sands from onshore test sites in New Jersey and from offshore wind lease areas across the Atlantic OCS, (ii) impact driving of steel pipe piles through glauconite / glauconitic sands, and (iii) axial and lateral load testing of these piles. This paper presents an overview of laboratory testing results on glauconite samples from New Jersey outcrop locations and from PIGS core samples, as well as from degraded material that was crushed during pile driving. Tests include geological age dating, morphological and microstructural analysis, chemical analysis, and geotechnical index testing. We discuss distinct behaviours associated with authigenic glauconite deposits (grains formed *in situ*) and allogenic glauconite deposits (grains reworked from older units and redeposited), the latter showing the impact of removing weaker glauconite particles through degradation or removing finer-grained particles through downstream sediment transport. Also, analysis of degraded glauconite sands sampled directly from pile walls illustrates the degree of crushing and associated changes in plasticity caused by pile driving. These observations are explained by differences in glauconite grain microstructure, age and maturity.

Keywords: US offshore wind; US energy market; laboratory testing; field testing; glauconite sand

1 INTRODUCTION

Offshore wind development in the U.S. has been focusing primarily on the North Atlantic and Mid-Atlantic Outer Continental Shelf (OCS). These regions are chosen due to their proximity to high energy demand areas, suitable shallow water depths, and strong wind conditions. The Atlantic OCS, designated as a 'frontier' region by the Bureau of Ocean Energy Management (BOEM), contains glauconite-rich sediments found in multiple lease areas. Glauconite is a friable green to black iron-potassium phyllosilicate mineral. This mineral exhibits unique behaviour under shearing: particle sizes are reduced, and this can transform glauconite-rich layers from a coarse-grained to a fine-grained soil. This transformation, with associated changes in stress conditions in the soil, can result in high soil resistance to driving (SRD) and can potentially lead to premature pile installation refusal (DeGroot et al., 2023).

To address these uncertainties, the Piling in Glauconitic Sand (PIGS) Joint Industry Project (JIP) was established in 2021 to better understand the behaviour of glauconitic soils around piles through site investigations, field scale testing, and data interpretation. The goal is to develop a framework for assessing the impact of glauconite sand on offshore wind infrastructure development, focusing on the Atlantic OCS. While recent publications have

addressed glauconite-related issues (Westgate et al., 2023; DeGroot et al., 2023) and provided early results from PIGS pile installation tests at an onshore site (Westgate et al., 2024), this paper presents insights from geological, microstructural, and geotechnical testing at test sites across New Jersey (NJ), with a particular focus on the implications for wind farm developments including those located directly offshore.

2 NEW JERSEY GLAUCONITE SANDS

Three locations across NJ were tested, all of which sit within a glauconite belt that extends from Massachusetts to Virginia. The main test site – Search Farm – was used to perform the pile installation and load testing program (Westgate et al., 2024; Pisanò et al., 2025). The other sites – Edelman Fossil Park and Poricy Park Fossil Beds – were sampled as part of the overall laboratory testing program. Two glauconite formations were investigated: the Paleocene Hornerstown Formation and the Cretaceous Navesink Formation. The Hornerstown Formation is a light green glauconite sand that was deposited during the early Cenozoic (66.0-61.5 Ma) on a continental shelf in 50 to 150 m of water. The Navesink Formation is a dark green to black clayey glauconite sand that was deposited during the late Cretaceous (70.5-66.0 Ma). The boundary between the Hornerstown and Navesink formations marks the Cretaceous-Paleogene (K-Pg) mass extinction event (Miller et al., 2010).

2.1 Search Farm, Cream Ridge, NJ

At Search Farm, the authigenic (*in situ*) Hornerstown and Navesink formations lie at depths from approximately 3.2 to 7.4 m and 7.4 to 19.5 m, respectively. All depths noted herein are below ground surface. There is a transitional unit from approximately 19.5 to 21.0 m comprising Navesink and reworked Mount Laurel Formation quartz sand from the Campanian (73.0-71.5 Ma). Core samples at the test site, as well as outcrop samples from ~300 m northwest along the eastern bank of Crosswicks Creek, were collected. At the outcrop, the Hornerstown is altered by surficial weathering, while the Navesink is slightly indurated.

2.2 Edelman Fossil Park, Sewell, NJ

This former Inversand Quarry was mined for glauconite sand and is currently operated as the Jean & Ric Edelman Fossil Park by Rowan University. It contains the Main Fossiliferous Layer (MFL) in the basal authigenic Hornerstown Formation, which lies at depths from approximately 10.2 to 16.1 m. It is heavily burrowed below 15 m with echinoid faecal pellets and clay blebs. The authigenic Navesink Formation starts at approximately 16.1 m depth and is heavily bioturbated with glauconite concentrated in burrows. Outcrop samples of both formations were extracted manually from the base of the archaeological excavation.

2.3 Poricy Park Fossil Beds, Red Bank, NJ

Fossil-rich beds are found in Poricy Park along Poricy Brook. While the Hornerstown Formation is not present, the authigenic Navesink Formation is exposed containing fossil beds at its base and grading up to silts and sands of the Red Bank Formation. Weathering has produced a ~50/50 mixture of eroded authigenic glauconite sand and quartz sand in the streambed. While the streambed deposits may be considered analagous to an allogenic (reworked) deposit, it may be more accurately described as an authigenic deposit which has simply lost its finer-grained material due to downstream sediment transport and mixed with a different source quartz sand during redeposition.

3 FIELD TEST PROGRAM

Site characterisation activities performed at Search Farm comprised ground penetrating radar, piezometric monitoring, standard penetrometer testing (SPT), seismic piezocone penetrometer testing (SCPTu), cone dissipation testing, Shelby tube and Denison tube sampling, and novel sampling of crushed glauconite soil adhered to the walls of the driven piles (Westgate et al., 2024). One of the smaller diameter (0.32 m) piles was vibro-extracted, allowing manual sampling of the shear zone along the pile. The larger diameter (1.52 m) piles were sampled using Shelby tubes along the inner pile wall. The glauconite sand formations at Search Farm are moderately dense yet show contractile behaviour within a localised hard layer. Further details on the field testing, including novel cone penetrometer testing to investigate mitigation of rod friction, are presented by Westgate et al., (2024) and Pisanò et al., (2025). *In situ* testing was not performed at the other test sites.

4 LABORATORY TEST PROGRAM

The laboratory test program comprised a wide range of geological tests, microstructure analyses, and

geotechnical tests, some of which are presented here. The objectives of the testing were to (i) provide data on the glauconite sands at the test site to support interpretation of pile installation data (Westgate et al., 2024) and load testing data (Pisanò et al., 2025), and (ii) develop laboratory testing procedures to allow simulation of pile installation effects and explore the impact of testing across a spectrum of authigenic and allogenic glauconite sands.

4.1 Geological age

Radiometric age-dating was performed to constrain glauconite source formations to aid the differentiation between authigenic and allogenic grains (e.g., Logvinenko, 1982). Conventional age-dating using potassium-argon (K-Ar) and argon-argon (Ar-Ar) methods have historically resulted in ages 5-10% younger than the true depositional age. Similarly, K-Ar dating performed on samples from the test sites revealed ages ranging from 44.0-66.0 Ma relative to a depositional age of 66.0-61.5 Ma, demonstrating the argon isotope loss through diagenetic processes.

4.2 Glauconite content

Glauconite content is a potential indicator of deposition history. Authigenic deposits generally have high glauconite content, whereas allogenic deposits are generally more variable and glauconite content and its distribution reflects sedimentary depositional processes. Three approaches to glauconite content determination are considered.

The first method is visual grain counting using a digital image analysis technique that identifies glauconite based on colour (King et al., 2023). This approach involves washing to remove fine-grained sediments (< 75 microns) and estimating the volume of glauconite through automated grain identification (i.e., digital segmentation) and classification. If the removed fines content is significant and its glauconite percentage is different to the remaining sand fraction, then estimations of glauconite content may be unreliable.

The second method is a non-destructive, weight-based estimation through magnetic separation of glauconite particles owing to their high iron content. Sylvia (2022) developed a magnetic separation procedure that avoids the abrasion produced in larger scale separators used in the mining industry. The technique is manually intensive, requiring washing (i.e., loss of fines may again impact the results) and requires several rounds of separation.

Comparisons between these two methods show reasonable agreement, and both approximate glauconite content as a function of particle size. A high coarse-grained glauconite fraction may indicate a high susceptibility to degradation as these grains could be crushed during pile driving.

A third approach to glauconite content estimation is X-ray diffraction (XRD) or X-ray fluorescence (XRF), which analyse the X-rays diffracted or emitted from powdered samples that are subjected X-ray energy. In powdered form, only the glauconite mineral content is detected, and the substrate material (e.g., foraminifera [calcium carbonate], faecal [organic] matter) and other constituent minerals are identified but not included with the glauconite mineral content. Hence, the results are biased towards lower glauconite content than image analysis or magnetic separation. Results from these X-ray methods help to understand the potential soil behaviour changes of degraded glauconite particles during or after pile driving.

4.3 Maturity

Odin and Matter (1981) established a maturity scale for glauconite particles based on potassium content, transitioning from nascent (< 4% K_2O) glauconitic smectite to slightly evolved (4 to 6%), evolved (6 to 8%), and finally highly evolved (> 8%) glauconitic mica. The tendency for iron and potassium to increase concurrently is well established, yet Baldermann et al. (2022) introduced aluminium and magnesium content as alternative indicators of maturity. Examination of relationships between K_2O, Fe_2O_3, Al_2O_3, and MgO reveal that ratios of K_2O to Al_2O_3 produce better agreement with glauconite maturity assessments compared to direct derivation methods using thin-section analysis. Glauconite content measured on Search Farm cores and (magnetically separated) Poricy Navesink ranged from 30% (slightly evolved) to 69% (highly evolved), corresponding to medium to coarse-grained glauconite fractions of > 90%.

Visible/near-infrared (VNIR) spectroscopy and inductively coupled plasma-optical emission spectroscopy (ICP-OES) offer a secondary approach for determination of mineralogy through comparison of spectral signatures. Surprisingly, most of the samples tested (both natural and powdered) did not produce good matches with the USGS glauconite reference spectra (HS313), instead indicating a wide range of clay minerals with no apparent trends among deposits tested that best matched the glauconite spectra. This suggests that it is not exclusively the glauconite mineral presence that exhibits high crushability, and perhaps glauconite particle

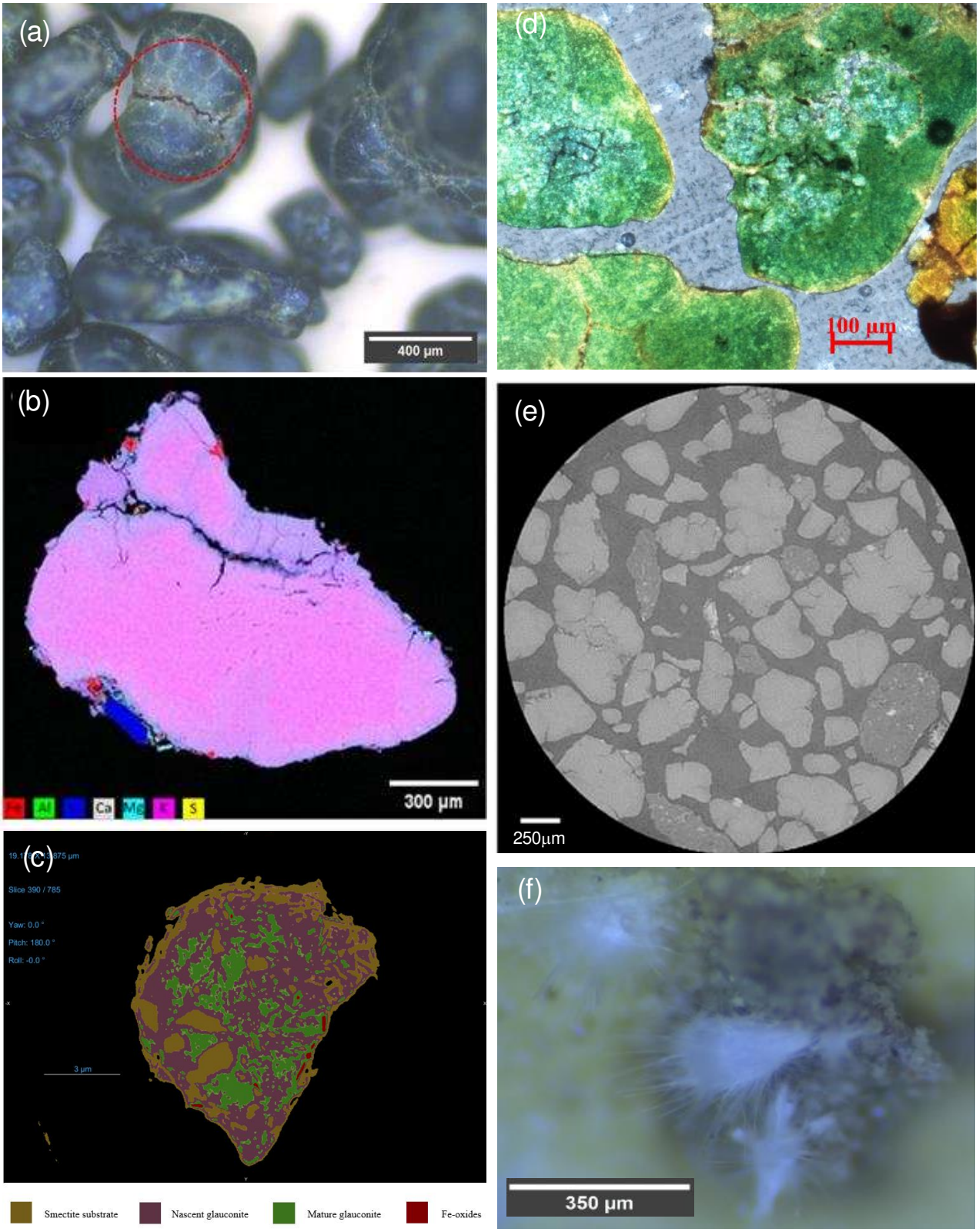

Figure 1. Poricy and Search Farm Navesink examples of microstructure analysis, showing (a) optical microscopy image of lobate grain shape and surface fracture on intact grain, (b) SEM-EDXS image showing locations of elemental composition, (c) mineral mapping of a nanoCT image, (d) thin-section image under cross-polarized light showing slightly evolved and evolved grain with clay and iron presence, (e) µCT image showing denser (brighter) glauconite particles among calcium carbonate and silica particles, and (f) optical microscopy image of precipitated salt crystals.

morphology and microstructure are influential characteristics. Figure 1 presents example images of Search Farm and Poricy Navesink particles from various microstructure analysis techniques including optical microscopy, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDXS), nano-chromatography (nanoCT), X-ray microtomography (μCT), and isolated microporosity (which measured from 1 to 6% for samples tested).

4.4 Chemical properties

Acidity (pH), salinity ($NaCl_2$) and carbonate content ($CaCO_3$) tests are routinely performed on soil samples and can provide insights into potential soil behaviour characteristics such as plasticity and strength. Figure 2 presents pH and salinity versus depth comparing cores, outcrops, and pile wall samples from Search Farm. The pH of the core samples is generally higher than the outcrop samples, with the former ranging from 4.5 to 6.8 in the Hornerstown Formation (compared to an outcrop acidity of 4.4) and from 2.6 to 7.8 in the Navesink Formation (compared to an outcrop acidity of 2.4). Pile wall samples show similar acidity to core samples in the Hornerstown, but higher pH (lower acidity) in the Navesink.

The salinity of the core samples is generally lower than the outcrops samples. Only one of the Navesink core samples exhibited such high salinity, occurring at a depth of 10.7 to 11.3 m associated with the indurated zone. Pile wall samples exhibited consistently lower salinity than the others, suggesting the crushing process releases trapped saltwater within the micropore spaces, which may partially explain the high positive pore pressures in the Navesink. The measured salinity of 36.2 ppt is also consistent with mean seawater for the Maastrichtian age (Late Cretaceous, ca. 71.5-66.0 Ma), raising the possibility that the induration of the Navesink has trapped connate (fossil) seawater. The lack of any salt content in the Hornerstown outcrop sample indicates modern groundwater percolation through the overburden, and to some degree through the Hornerstown Formation at the core locations.

Only one core sample – the Navesink Formation just below the hard layer at about 16 m depth – showed carbonate content > 10%, classifying as *calcareous* (Clark and Walker, 1977). This is likely due to groundwater leaching down through the hard layer, which included ancient shells. Pile wall samples show similar low carbonate content to the outcrops and cores (~3-4%).

4.5 Grain size evaluation

Previous related work provided insights into the effects of specimen preparation, drying time, and mixing time (via artificial degradation in an ASTM dispersion cup with slurry mixing times of 10 minutes and 60 minutes compared to the standard ASTM hydrometer mixing time of 1 minute), showing that glauconite sand is subject to large changes in fines content and clay fraction during shear (McMullin, 2023; Westgate et al., 2023; DeGroot et al., 2023).

Figure 3 compares changes in fines content across the three sample types at Search Farm. The Hornerstown outcrop sample has an unusually high fines content compared to the cores, reflecting the greater degradation of glauconite in the outcrop due to weathering and groundwater flow. The Navesink outcrop is more resilient due to its greater maturity but also shows higher fines content compared to core samples. The particle size distributions (PSDs) from the pile wall indicate only slight increases in fines content. However, testing individual layers at different radial offsets from the pile wall shows higher degradation immediately adjacent to the pile wall (Figure 4), with the range of observed degradation equivalent to between 1 minute (furthest from pile wall) and 60 minutes (closest to pile wall) of dispersion (Hamilton, 2024).

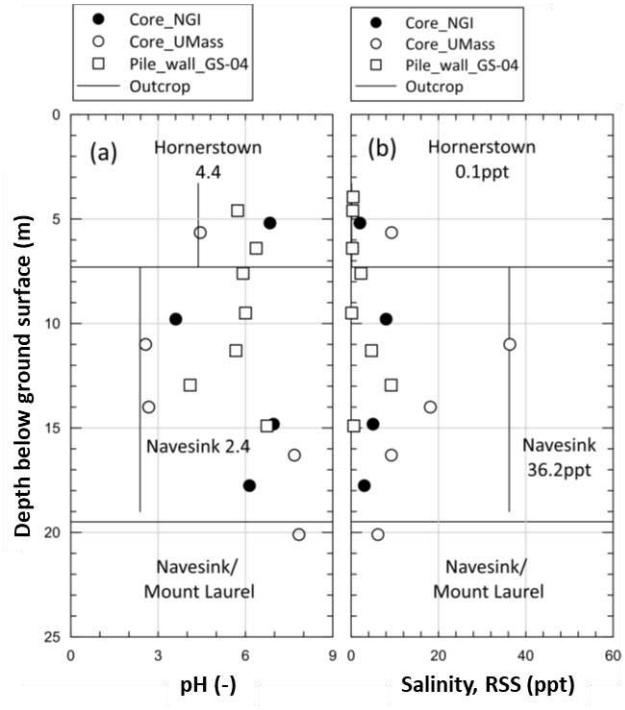

Figure 2. Chemical properties of Search Farm samples.

The least amount of degradation was observed for the sample obtained from the tip of the larger diameter pile (GS-04), which suggests crushing continues along the shaft as the pile is driven deeper.

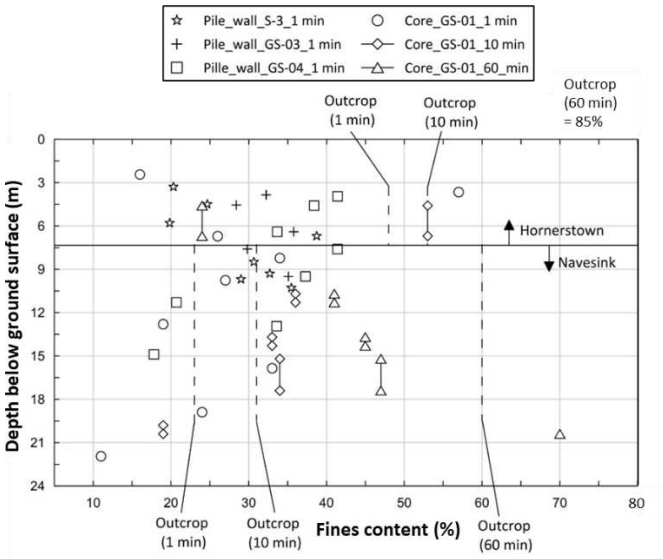

Figure 3. Fines content comparison at Search Farm

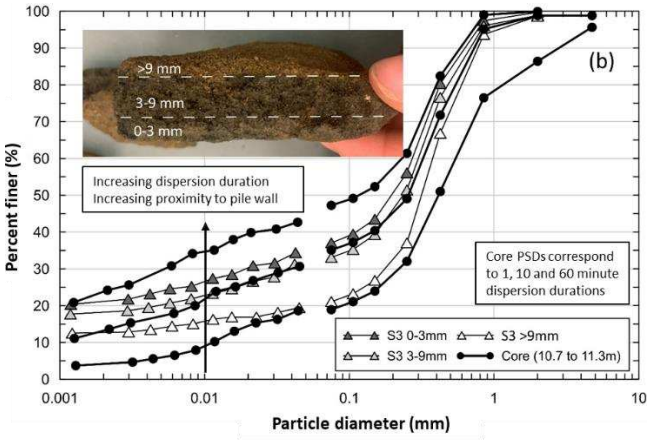

Figure 4. Pile wall sample PSDs compared to core samples

4.6 Plasticity

Atterberg limits of glauconite sands are affected by prior degradation and deposition history (DeGroot et al., 2023), with authigenic glauconite transitioning from (USCS) coarse-grained (SP, SM or SC) to fine-grained (ML, MH, CL or CH) depending on the dispersion time, and allogenic samples showing fewer changes in plasticity. Figure 5 compares liquid limit (LL) and plastic limit (PL) across the three types of samples at Search Farm; also included are limits performed at 10 minute and 60 minute dispersion on outcrop samples. The outcrop samples in both Hornerstown and Navesink formations showed the greatest increases in plasticity compared to the core samples, consistent with their weathered/indurated conditions. In situ water contents of the pile wall samples and cores (closed symbols) are close to the plastic limits, suggesting that extended dispersion may not simulate the degradation process occurring in the field, where free water is limited.

Interestingly, samples which were not passed through the No. 40 sieve as per ASTM D4318-17 procedures showed a wider range in plasticity in the Hornerstown Formation, whereas corresponding samples in the Navesink Formation showed a narrower range. This shows that the particles most susceptible to degradation within the Hornerstown Formation were larger than the particles most susceptible to degradation within the Navesink Formation, suggesting that the ASTM (2017) procedure may underpredict glauconite degradation in some deposits.

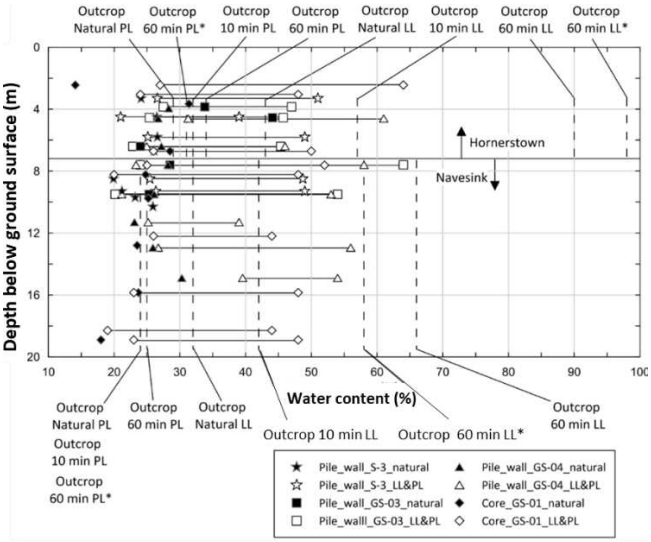

Figure 5. Atterberg limits comparison from Search Farm samples

4.7 Particle strength

Single particle crushing test results for glauconite grains show Weibull survivability (i.e., 37% characteristic) strength values of 5 to 8 MPa for the Hornerstown Formation and 7 to 10 MPa for the Navesink Formation across all three sites, the latter being slightly stronger than the former due to its greater maturity. The Poricy Navesink was the strongest among the glauconite samples, possibly due to weaker and/or finer particles being transported away from the deposit, leaving stronger particles behind.

These values compared similarly to carbonate sand, e.g., with Weibull (37%) strength values ranging from 2 to 26 MPa (Beemer et al., 2019). While crushing of carbonates is often attributed to high angularity and low internal porosity, crushing of glauconite is more influenced by its agglutinated structure and grain cracks and fissures.

5 CONCLUSIONS

An extensive laboratory test program including geological tests, microstructure analyses, and geotechnical tests were performed on glauconite sand samples from test sites in NJ as part of the Piling in Glauconitic Sand (PIGS) Joint Industry Project. The following insights are shared.

Geological age-dating is useful for identification of authigenic and allogenic history if source deposits are known. It is important to supplement age-dating with mineralogical analysis (e.g., XRD, XRF) to understand the particle's maturity. Spectroscopy should not be used alone as this may underestimate glauconite presence. Glauconite content by coarse-grained fraction is important for assessing potential glauconite degradation, while glauconite mineral content is important for assessing degraded glauconite behaviour. Microstructure analysis can detect mineral presence through the particle and extent of fissures and cracking. Thin section analysis is the most reliable approach to assess glauconite maturity, but use of alternative ratios of key minerals (K_2O/Al_2O_3) shows promise as a reliable secondary indicator.

Artificial glauconite sand degradation in the laboratory can be used as a proxy for crushing below and along the pile due to impact driving. Based on measured PSD from pile wall samples extracted at the test site, mixing in an ASTM dispersion cup from the standard 1 minute up to 60 minutes captured the range of degradation from pile driving, and this was found to vary among glauconite units. However, the presence of water may enhance changes in PSD through release of the clay minerals. Changes in plasticity resulting from finer gradation is greatest for younger, less mature, authigenic deposits. Particle strength of glauconite sands tested are lower than some carbonate sediments. Allogenic particles are less vulnerable to degradation than authigenic particles, as the reworking process leaves only the stronger particles behind.

AUTHOR CONTRIBUTION STATEMENT

Z. Westgate: Conceptualization, Overall data curation, Formal analysis, Funding acquisition, Project management, Writing - Original draft. **Other Authors**: Conceptualization, Geotechnical data curation, Writing - Reviewing and Editing.

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