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14. ABSTRACT Coastal margins and tidal flat sediment systems are some of the most complex, heterogeneous and energetically dynamic regions on earth. Tidal flats are repositories of terrigenous and biogenous sediments that are shaped by tides, waves and storms and utilized by birds and benthic organisms. They often lie adjacent to rivers that enable inland passage for ships and access to spawning grounds for fish. As such, they are subject to numerous anthropogenic effects, such as fishing, clamming, beach combing, and automobile traffic. Depending on their morphology and tidal range and periodicity, tidal flats are inundated or exposed for variable amounts of time and over widely different areas. To better understand the properties and distribution of the sediments within this setting, an ongoing study is being conducted to determine the relationship between thermal and geotechnical properties of tidal flat sediments. Our specific objectives are: 1) to determine how to assess thermal properties of laboratory-simulated tidal flat sediments and 2) to assess the relationship between sediment composition and undrained shear strength. The ultimate goal of these efforts is to remotely predict tidal flat trafficability (humans or vehicles) from the temperature signature. To understand how mineralogy influences thermal properties of sediments, several sediment types were tested. To simulate the heterogeneity of the tidal flat, a					
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Thermal diffusivity and strength of tidal flat sediments during a tidal simulation

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Abstract-

Coastal margins and tidal flat sediment systems are some of the most complex, heterogeneous and energetically dynamic regions on earth. Tidal flats are repositories of terrigenous and biogenous sediments that are shaped by tides, waves and storms and utilized by birds and benthic organisms. They often lie adjacent to rivers that enable inland passage for ships and access to spawning grounds for fish. As such, they are subject to numerous anthropogenic effects, such as fishing, clamming, beach combing, and automobile traffic. Depending on their morphology and tidal range and periodicity, tidal flats are inundated or exposed for variable amounts of time and over widely different areas. To better understand the properties and distribution of the sediments within this setting, an ongoing study is being conducted to determine the relationship between thermal and geotechnical properties of tidal flat sediments. Our specific objectives are: 1) to determine how to assess thermal properties of laboratory-simulated tidal flat sediments and 2) to assess the relationship between sediment composition and undrained shear strength. The ultimate goal of these efforts is to remotely predict tidal flat trafficability (humans or vehicles) from the temperature signature. To understand how mineralogy influences thermal properties of sediments, several sediment types were tested. To simulate the heterogeneity of the tidal flat, a range of sand-clay mixtures was evaluated. The sand-clay percentages in these mixtures ranged from 100:0 to 0:100 with fractional percentages decremented or incremented by 10 or 20% until all possible sediment mixtures were achieved. Though more complicated scenarios can be simulated, the initial experiments only considered fully saturated sediments. Each sediment tested was exposed to a heat lamp and the resulting temperature gradient was measured every two centimeters with a vertical thermistor array. Measurements were recorded at 5-second intervals during a warming cycle ($\sim 20^{\circ}\text{C}$ change in temperature) and were used to calculate the thermal diffusivity of the sediment using the one-dimensional heat equation. To mimic lateral continuity of a real-world tidal flat and to satisfy the one-dimensional requirement of our numerical method, the sediment was insulated on its sides and base while remaining open at the top to a focused heat source. Homogeneous sediments of varying mineralogy showed distinct differences in thermal conductivity. The ratio of saturated and dry conductivities for sand was 3 times greater than the same ratio for kaolin, suggesting that measurements of sediment temperature at high and low tides might provide insight to tidal flat sediment type. Furthermore, data collected with sediment mixtures showed a non-linear decrease in thermal conductivity with increasing clay fraction and an inverse relationship between thermal conductivity and shear strength. Finally, sediment bearing capacity and shear strength increased with packing density with the highest shear strength occurring at depth within the sediments. The greatest difference in sediment strength occurred in the pure clay sample with the surface strength being $\sim 53\%$ lower than the strength at 10 cm below the surface. Additionally, as clay content increased, sediment strength increased as well. On going work will continue to evaluate the relationship between thermal and geotechnical properties of tidal flat sediments. Field work will be conducted in the upcoming months to assess whether thermal properties of sediments may be correlated with sediment strength and trafficability.

I. INTRODUCTION

The variability of thermal diffusivity, or heat transfer, due to soil properties has been widely evaluated within the soil sciences in order to address crop potential. Despite this link, the influence of coastal and marine sediment properties on thermal diffusivity has been evaluated far less frequently even though variability in thermal diffusivity and biologic activities might be related. Recently, thermal signatures have been evaluated to determine sediment classes by quantifying surface temperatures over a tidal cycle; in these studies, the thermal signature of surface sediments was determined to differ due to water retention and mineralogy [2-3] but it is unclear how the thermal signal relates to sediment variability. A means to remotely assess the thickness of these deposits would provide critically needed information on sediment bearing strength within these incredibly complex environments [4] (Fig. 1). If a relationship between heat flux and various sediment properties (e.g. water content, grain size and mineralogy) can be established, simple measurements of vertical temperature gradients over time may enable remote classification of tidal flat bearing strength and trafficability.

Currently, it is relatively easy to differentiate pure sand from pure clay deposits due to differences in water content [2-3]. What is less apparent is how to use the thermal signature to infer sediment and geotechnical properties for mixed sediments with a range of mineralogies and variable proportions of sand and clay. We suggest that measurements of thermal diffusivity may

provide valuable insight into sediment and geotechnical properties of a tidal flat, provided the interplay between the components of these sediments (i.e., water content, sediment homogeneity or heterogeneity, mineralogy) is more thoroughly understood.



Figure 1. Tidal flat composed of sand (background) and mud (foreground). Support of the vehicle that left the track was possible because the mud is underlain by sand (as seen in background). Our research suggests that the thermal signature of sediments may be related to their geotechnical properties, potentially enabling remote characterization of trafficability on tidal flats such as this one.

A field-based assessment of the relationship between thermal and geotechnical properties is difficult. This is mostly due to the fact that tidal flats are very dynamic and too many of the variables that influence heat flux and sediment strength cannot be isolated. First, tides, waves, and river discharge are constantly reworking sediment deposits through accumulation and erosion. This leads to temporal and spatial variability in tidal flat composition, accumulation rates and dewatering or compaction, which are all variables that could affect thermal diffusivity and geotechnical properties. Simultaneously, tidal flat sediments are acted upon by a multitude of biologic forces (i.e., mucopolysaccharides excreted by benthic organisms bind sediment together) that may enhance sediment strength, alter bed surface morphology, modify fluid flow and sediment transport which may in turn change thermal diffusivity and geotechnical properties. Furthermore, tides alternately expose and inundate sediments as much as twice daily and the magnitude of this effect varies with storms and seasons. Before inroads can be made in understanding (the likely) non-linear relationships between thermal and geotechnical properties of *in situ* tidal flat sediments, laboratory simulations that isolate specific variables can provide baseline information that will lead to improved interpretations of tidal flat geotechnical variability from remotely sensed thermal imagery. The goal of our current study is to determine how sediment variability affects the thermal and geotechnical properties of laboratory-simulated tidal flats. A laboratory approach allows for elimination of much of the environmental variability inherent to tidal flats, which enables us to isolate and quantify the thermal response as a function of sediment type and composition. Additionally, our results can provide well-controlled boundary conditions for one- and two-dimensional heat flow models used to simulate more complicated scenarios.

II. METHODS

Sediments used in initial experiments were chosen to simulate the range of grain sizes and mineralogies typical of tidal flat environments. Baseline thermal diffusivities (e.g. 100% dry & 100% saturated) were determined for each sediment type (i.e., kaolinite, quartz sand, bentonite, strontium carbonate and iron oxide). Because tidal flat sediments are often distributed across grain size classes, mixtures of sand and clay (clay being either kaolinite or bentonite) were also prepared with sand:clay ratios ranging from 100:0 to 0:100. These samples were fully mixed using a rotary drill to achieve a homogenized sample that lacked stratigraphic layering. Data for the saturated sediments was collected using the same sediments used for the dry tests, but saturated with tap water.

The sediment of interest was added to a two-gallon bucket, which was then inserted into a cooler filled with foam insulation (Fig. 2). An 8-thermistor array was inserted into the sediments at the center of the bucket (Figs. 2 and 3). The uppermost thermistor recorded temperature changes approximately 1 cm



Figure 2. Bucket of kaolin clay that is insulated from horizontal heat flux by the cooler. A thermistor array is inserted into the clay in the center of the bucket. The rainbow ribbon cable transmits temperature readings to the data recorder every 5 seconds during a cooling or warming cycle. This set-up minimizes two-dimensional heat conduction.

above the sediment surface, while the other seven thermistors recorded vertical temperature changes every 2 cm in the sediments (Fig. 3). A heat lamp located ~30 cm above the sediment served as the temperature forcing and warmed the sediments for ~3 hours (Fig. 3). By measuring vertical temperature changes over time, we were able to use the one-dimensional heat equation to calculate thermal diffusivity (α),

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \quad (1)$$

where T is temperature ($^{\circ}\text{C}$), t is time (s), z is depth (cm), and α is thermal diffusivity (cm^2/s). Thermal diffusivity is related to thermal conductivity as follows:

$$\alpha = \frac{\lambda}{\rho_b c_p} \quad (2)$$

where λ is thermal conductivity ($\text{W/m}\cdot\text{K}$), ρ is bulk density (kg/cm^3), and c_p is specific heat capacity ($\text{J}/\text{kg}\cdot\text{K}$). The thermal conductivity was then calculated for each simulated sediment using our estimate of thermal diffusivity, a measurement of the bulk sediment density (at the surface and at 10 cm depth using a Quantachrome Pentapycnometer), and reported values for specific heat capacity. Because our numerical method is one-dimensional, we took care to minimize the horizontal heat gradient in our experiments. By putting the sediments inside the cooler and focusing the energy from the heat lamp directly over the sediments, we ensured that our experiments were as one-dimensional as possible. Our experimental determinations of thermal conductivity,

using a discretized heat equation, were substantiated by direct measurements of thermal conductivity using a standard probe (Hukseflux® TP-02). The probe is comprised of a needle that sends a preset heat pulse and records the decay of this heat pulse to determine the thermal conductivity of the sediment.

To obtain geotechnical data, shear strength was measured on fully saturated samples using a standard shear vane equipped with a 1 cm vane. Measurements were made at 0-1 cm and 10-11 cm below the sediment surface. Samples that contained 80 to 100 % sand were not evaluated with the shear vane. SWD-Collect by Labtronics Inc. was used to collect the shear vane rotation data and Igor® Pro, Wavemetrics Inc. was used to process and plot the vane shear data. From these plots of vane shear, the critical shear strength of each sample was obtained; the critical shear strength is reported here as it demarks the change from elastic to plastic deformation of the sediments.

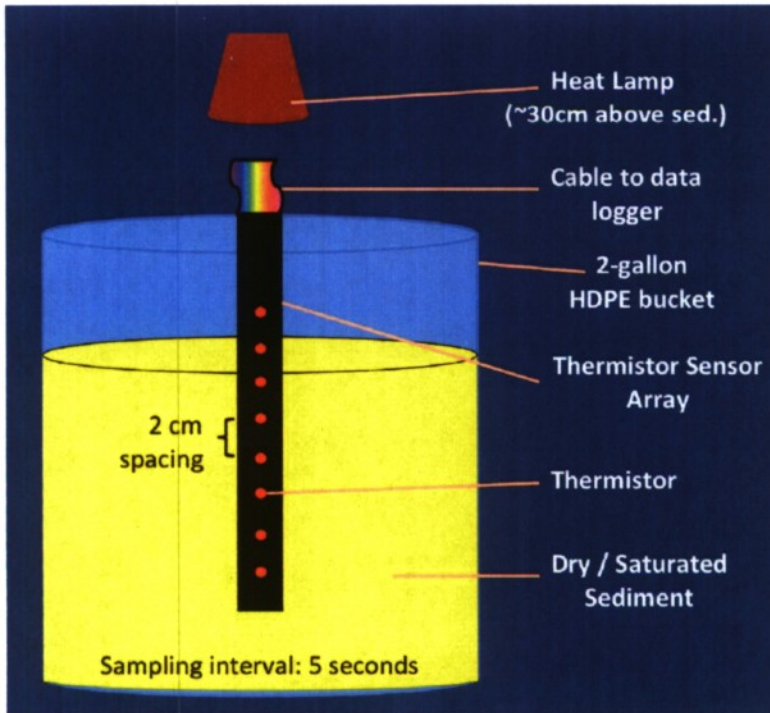


Figure 3. Cartoon of the thermistor array within a bucket of sediment. The red dots represent thermistors that are spaced at 2 cm intervals with one thermistor just above the sediment and the rest buried at different depths within the sediment. The sediments are either dry or saturated, depending upon the experiment. The heat lamp focuses energy at the surface of the sediments. The rainbow colored wires provide a link to the data logger which records temperature for each thermistor every 5 seconds. This whole system is placed within the insulated coolers (Fig. 2).

III. RESULTS

Not surprisingly, adding water to dry, pure sediments significantly changed their thermal properties. However, the magnitude of the change varied between different mineralogies. The individual conductivities and the ratio of saturated:dry thermal conductivity for each sediment type tested are shown in Table 1. Note

Sediment Type	Dry Conductivity (W/m K)	Saturated Conductivity (W/m K)	Ratio (Sat:Dry)
Sand	0.35	4.00	9.0
Kaolin	0.19	0.78	2.9
Strontium Carbonate	0.12	0.49	4.1
Iron Oxide	0.18	0.93	5.2

Table 1. Variability in dry and saturated thermal conductivities for each sediment type tested. Note that while the dry conductivities are similar, the addition of water significantly changes the thermal behavior of each sediment, especially sand. Saturated:dry thermal conductivity ratios indicate that thermal signatures of dry and saturated sediments may be useful for predicting mineralogical variability on tidal flats.

Mixture (% Sand)	Thermal Conductivity (W/m K)	Undrained Shear Strength (kPa)
100	2.79	N/A
90	1.52	N/A
80	1.04	0.69
60	0.84	0.86
50	0.79	0.88
40	0.76	0.96
20	0.68	0.95
0	0.65	1.21

Table 2. (left) The relationship between sand:clay mixtures for thermal conductivity and undrained shear strength. The decrease in thermal conductivity with a decrease in sand % is clear until sand concentration reaches and falls below 60%. Conversely, as sand concentration decreases sediment shear strength increases. The shear strength was not determined for samples with <10% clay and is of questionable validity for samples with 20% clay.

Table 3. (below) Sediment strength of sand:bentonite mixtures as a function of depth. Shear strength was not determined for sand:clay mixtures for which the sand percentage exceeded 70%.

Surface Strength			Strength @ 10cm below surface		
% Sand	kPa	± 1 SDev	% Sand	kPa	± 1 SDev
100	ND	ND	100	ND	ND
90	ND	ND	90	ND	ND
80	ND	ND	80	ND	ND
60	0.86	0.02	60	2.39	0.09
50	0.88	0.03	50	3.21	0.17
40	0.96	0.03	40	2.40	0.12
20	0.95	0.03	20	2.06	0.08
0	1.21	0.32	0	2.59	0.07

that the ratio for sand is approximately 3 times that of kaolin.

Results from the experiments using mixtures of sand and bentonite showed an inverse relationship between thermal conductivity and undrained shear strength (Table 2). First, the thermal conductivity is markedly reduced from the value of pure sand with only a small increase in clay (e.g. 2.79 W/m·K for pure sand versus 1.52 W/m·K for 90% sand, 10% clay). Overall, thermal conductivity decreases with increasing percentages of clay though it is important to note that the trend is not linear (Table 2). The opposite is true for undrained shear strength, which increases with increasing percentages of clay.

Finally, shear strength as a function of depth also varied with decreasing % sand (or increasing % clay). Results are shown in Table 3. At the surface, shear strength increased with increasing fraction of clay as might be expected. The strength at 10 cm below the surface of the sediment increased by about a factor of 2, but did not show as strong a relationship with increasing clay fraction.

IV. SUMMARY AND CONCLUSIONS

Tidal flats are complex sedimentary environments in which subaerial and subaqueous processes change sediment properties over very short time scales. We propose that the distinct thermal behavior of different sediment assemblages might help us remotely monitor the spatial variability of sedimentological and geotechnical properties of tidal flats. We established a methodology that

allowed us to simulate a simplified tidal flat environment in the laboratory (one-dimensional heat flux) and evaluate the thermal characteristics of sediments with variable mineralogy and variable percentages of sand and clay.

Our initial experiments showed that thermal diffusivities and conductivities are very similar (within a factor of 2) for the dry sediments of various mineralogies (Table 1). Substantial variations (greater than a factor of 4) were observed for saturated sediments (Table 1). This response suggests that the ratio of saturated to dry conductivities might be used as an indicator of sediment type. To do so operationally would require observations around low and high tide necessitating periodic observations that are coincident with high and low tide. Because this method requires that there is a strong vertical gradient in temperature, thermal measurements would likely have to be made during the day when the sun heats the sediments. It is important to note that these simulations do not account for advective processes that are likely to be important causes of heat transfer during rising and falling tides.

The bimodal distributions that were evaluated in this study represent grain size distributions more common to tidal flat environments. First, it is important to note that the relationship between saturated sediment composition and thermal conductivity is not linear (Table 2) as has been assumed in the past [2]. Applying a simple linear thermal model to tidal flats that encompass pure clay and pure sand end-members may fail to capture relevant trends that occur in mixed sediments. Using these data and observations from future experiments, we hope to quantify the influence of compositional changes of tidal flat sediments on thermal conductivity.

Additionally, we have shown that sediment shear strength increases as thermal conductivity and % sand decreases (Table 2). This relationship suggests that sediment shear strength on a tidal flat might be predicted from observations of temperature gradients within the sediments. If this is the case, then bearing capacity of these same sediments, which has been clearly correlated with shear strength [6], might be predicted using remotely obtained thermal signatures from tidal flats. However, given the simplicity of our simulations and the complexity of the tidal flat environment, more work is necessary to more thoroughly evaluate this relationship. Future work, including more laboratory experiments, field tests, and numerical modeling, will provide a better assessment of the utility and feasibility of this technique for remote characterization of geotechnical properties of tidal flats.

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