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Mechanical, Thermal, and Electrical Properties of Hydrate-Bearing Sediments

J.C. Santamarina[1], F. Francisca[1], T.-S. Yun[1], J.-Y. Lee[1], A.I. Martin[1], and C. Ruppel[2]

Civil and Environmental Engineering[1] and Earth and Atmospheric Sciences[2],
Georgia Institute of Technology, Atlanta, GA 30332

In any geologic settings, the complete characterization of the natural gas hydrate system requires an overlapping approach that includes direct sampling, downhole logging, and geophysical remote sensing. Due to the difficulty and cost of obtaining seafloor samples, scientists ultimately aspire to extract maximum information from downhole logs and geophysical data. Unfortunately, the inherent complexity and heterogeneity of natural systems often renders the interpretation of such indirect data difficult. As a means of calibrating logs and geophysical techniques, there is an important role for laboratory studies on controlled systems with known grain characteristics, formation history, and gas hydrate concentration. Such laboratory efforts lead not only to new effective media and mixture models that can be extended to interpret natural sediments, but also to a better mechanistic description of the interaction between hydrate and sediments.

We have conducted an extensive series of laboratory experiments to measure the thermal, electrical, and mechanical properties of fully saturated, homogeneous sediments containing synthesized THF hydrate, with support from the *ChevronTexaco Joint Industry Project (JIP) on Methane Hydrates*. Test conditions span most of the range represented in natural marine sediments (grain sizes of 1 to 120 μm), gas hydrate concentrations of 0% to 100% in pore space, and effective confining pressures of up to 2 MPa. The suite of laboratory measurements is summarized in the table on the last page.

Various cells are used to simulate the stress and strain fields in situ. These cells include a zero-lateral strain oedometer and axisymmetric triaxial and isotropic loading devices. Care has been taken to demonstrate reproducibility of the results, to calibrate equipment, and to maintain close temperature control on samples.

The laboratory experiments have produced data that constrain many key parameters, including thermal conductivity; electrical resistivity, and real permittivity in the 200 MHz to 1.3 GHz range; small-strain mechanical properties such as P- and S-wave velocities; volume change during compaction and during phase transformation; and large-strain mechanical properties including stress-strain curves and failure envelopes. In addition, the laboratory program includes a significant number of low-perturbation process monitoring studies, where hydrate formation and dissociation in sediment are carefully

followed. Finally, we have conducted detailed specimen dissection to explore the homogeneity of gas hydrate distribution in the sediments and the locus of gas hydrate formation.

We use four distinct homogeneous sediments for this study: Ottawa sand, precipitated silica flour, crushed silica flour (silt), and kaolinite (clay). The sediments were chosen to capture a wide and representative range of grain sizes (from 120 μm sand to ~1 μm clay) and specific surface (from ~$2x10^{-2}$ m^2/g to ~35 m^2/g). While the nominal grain size of precipitated silica flour is ~20 μm, its high specific surface (~6 m^2/g) leads to extensive internal porosity.

While THF is a Structure II, not Structure I (like methane), hydrate-former, it offers important advantages for laboratory studies. First, THF hydrate is stable under easily obtainable pressure and temperature conditions. Second, owing to the complete miscibility of THF in water, we have relatively good control on the amount of hydrate formed in each sediment sample, a goal that has proved elusive in some other laboratory efforts. Third, in contrast to the current generation of laboratory methane hydrate experiments that must resort to unsaturated media in order to form hydrate from aqueous phase methane, we can form hydrate from aqueous phase THF in fully saturated sediments. Fourth, the complete miscibility of THF in water allows specimen preparation in short laboratory time scales. In contrast, the low solubility of methane leads to a diffusion-limited system characterized by very large time scales for hydrate formation. While we recognize that there are potential differences between methane and THF hydrate and their interaction with the sediment, these laboratory experiments yield unprecedented insight about the relative importance of effective stress, grain size, specific surface, and hydrate fraction in affecting the bulk electrical, thermal, and mechanical properties of hydrate-bearing sediments.

This presentation highlights some of our key results and observations, which include:
- Complex behavior of thermal conductivity. In general, the thermal conductivity increases with confinement in all specimens without hydrate (unfrozen). For specimens with hydrate, the thermal conductivity reflects the competing effects of the thermal conductivity of the phases involved, their volume fraction and their spatial distribution.
- The small-strain stiffness, as detected with P- and S-waves, exhibits two regions: the hydrate-dependent region and the stress-dependent region. The transition from one region to the other shifts to higher confining stress as the hydrate fraction increases. At low and intermediate confinement, hydrate formation determines the small-strain stiffness of sediments, independent of the sediment type and porosity.
- Peak strength increases with the hydrate fraction and confining pressure. Strain localization initiates before the peak strength is reached and affects the failure mode.
- The real permittivity is controlled by the volume fraction of unfrozen water, and it readily reflects porosity reduction during compaction and hydrate formation.
- The electrical conductivity is controlled by the availability and mobility of ions. A gradual reduction in conductivity is measured during hydrate formation even

though ion exclusion keeps available ions within the unfrozen water. A drastic decrease in electrical conductivity is found in specimens with 100% hydrate-filled porosity.

- In general, the characterization of hydrate bearing sediments with elastic and electromagnetic waves yields complementary information.
- Other unique phenomena are observed, including non-recoverable deformation of the sediment matrix associated with hydrate formation and dissociation.

The data set has important implications for the calibration and interpretation of geophysical measurements and downhole logs collected in gas hydrate provinces, providing particular insight to the interpretation of P- and S-wave data and resistivity logs. In addition, the extensive new constraints on elastic moduli and strength parameters can lead to a revised consideration of seafloor/slope stability issues in areas with hydrate-bearing sediments.

Next page. Laboratory experiments completed as part of the Georgia Tech-JIP gas hydrate characterization project. Boxes containing multiple symbols have data from multiple experiments. Dark gray boxes denote experiments that were not conducted since the samples contain no hydrate. Light gray boxes represent experiments that were not possible due to the limitations of laboratory instrumentation.

Legend: o = single data point; oo = multiple data points; ▓ = dark shaded cell; ▒ = light shaded cell.

Material and Properties (grain size in microns; Sa=specific surface)	Target Hydrate Concentration (%)	EFFECTIVE Confining Pressure (MPa)	Longitudinal and lateral stress-strain	Elastic-Plastic Transition	Tensile strength (indirect)	Shear strength	Compressive strength	Failure/stability envelopes	Bulk moduli static	Triaxial compaction coefficient	Young's modulus static	Volume-Pressure compaction curves	Thermal Conductivity	Volume change - phase transformation	P-wave velocities, modulus/impedance	S-wave velocities, modulus/impedance	Bulk moduli dynamic	Electrical Resistivity	Real permittivity 200 MHz - 1.3 GHz	Hydrate distribution (optical/visual)	Pore filling vs. grain boundaries
SAND 120 µm Sa<<2.4e-2 m²/g	0%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		2.00										o	▒	▓	o	o	o	▒	▒	▓	▓
	50%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o			oo	oo
	100%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o	▒	▒	oo	oo
PRECIP. SILICA FLOUR 20 µm Sa=5-7 m²/g	0%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		2.00										o	▒	▓	o	o	o	▒	▒	▓	▓
	50%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o			oo	oo
	100%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o	▒	▒	oo	oo
CRUSHED SILICA FLOUR [SILT] 20 µm Sa< 1 m²/g	0%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		2.00										o	▒	▓	o	o	o	▒	▒	▓	▓
	100%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o	▒	▒	oo	oo
CLAY 1.1 µm Sa=35-37 m²/g	0%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	▓	o	oo	o	o	o	▓	▓
		2.00										o	▒	▓	o	o	o	▒	▒	▓	▓
	50%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o	▒	▒	oo	oo
	100%	0.01	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		0.50	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		1.00	o	o	o	o	o	o	oo	o	o	oo	o	o	o	oo	o	o	o	oo	oo
		2.00										o	▒	o	o	o	o	▒	▒	oo	oo