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Geotechnical Characterization of Laponite as Transparent Clay Surrogate

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Reference

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ABSTRACT

The use of so-called "transparent soils" as proxy geotechnical materials has allowed for the nonintrusive observation of a variety of models representing different engineered systems. Laponite is one such soft clay surrogate that has seen increased usage in recent years. However, this material has yet to be subjected to a thorough characterization and quantification of its physical and mechanical properties. The study presented herein followed a systematic approach toward the characterization of Laponite RD colloids from a geotechnical perspective across a wide range of mixes and additive dosages. Rheology tests were conducted to study the variation in apparent viscosity with time and after remixing. These tests identified two sources/types of strength gain: a reversible thixotropic strength gain and an irreversible particle aggregation strength gain. Different mixtures tested in a one-dimensional consolidation oedometer showed that mixes with laponite colloid contents as high as 21 % could be achieved from mixes with an initial colloid content of 11 % by mass. Finally, results from vane shear tests showed that the undrained shear strength increased with: (1) increasing laponite colloid content, (2) decreasing additive dosage, (3) aging time, and (4) increasing temperature. The base geotechnical characteristics and mechanical properties of the clay surrogate as provided in this study are expected to facilitate proper interpretation of the behavior of this surrogate material in geotechnical physical models involving transparent clays.

Keywords

transparent soils, Laponite RD, soft clays, geotechnical characterization, undrained shear strength

Introduction and Background

Transparent soils have been the subject of a number of geotechnical studies in recent years. Such materials have been used to visualize variations in the internal structure of soils during loading, including the associated localized internal displacements. This can be achieved by combining the transparent nature of these soils with the use of seeding particles and laser-based tracking tools and techniques.

Efforts toward visualizing, capturing, or measuring (or combinations thereof) internal deformations, changes in particle arrangement, and fluid flow patterns within soil samples are not new. Early studies involved methods based on X-ray radiography (Bergfelt 1956; Robinsky and Morrison 1964; James and Bransby 1970), time-domain reflectometry (Orsi et al. 1992), and nuclear magnetic resonance (Ng, Kelley, and Sampson 1996). The concept of nonintrusive measurements using a transparent material behaving as a soil surrogate was first introduced by Wakabayashi (1950), whose study involved mixing glass beads with a liquid of the same refractive index but showed poor transparency. Subsequent studies were conducted using a similar approach but achieving equally poor transparency (Chen and Wada 1986; Brock and Orr 1991). Significant improvements involving the use of different materials and approaches have since been reported by Iskander (2010). Consistent with the recent advances, transparent soil surrogates can be grouped into five categories: (1) amorphous silica powder that behaves like clays (Iskander et al. 1994); (2) transparent silica gels that behave like sands (Iskander, Sadek, and Liu 2002); (3) aquabeads that can be used to model flow in porous media (Tabe 2015); and (4) fused quartz, suitable for modeling the geotechnical properties of sands (Ezzein and Bathurst 2011). (5) More recently, a fifth group known as clay surrogates has emerged and involves the use of transparent synthetic clays (Beemer and Aubeny 2012), which involves the use of laponite colloids, a manufactured, synthetic product involving magnesium lithium phyllosilicate (MLPS) that is similar to natural hectorite clays (e.g., Wallace and Rutherford 2015; Beemer et al. 2016; Ads, Iskander, and Bless 2020a).

When mixed with water, laponite white powder results in a transparent synthetic clay material. This material exhibits very low undrained shear strength values, comparable with those of soft marine clays. A series of published studies have documented efforts to establish geotechnical properties of laponite mixes (Wallace and Rutherford 2015), assess their transparency (Yi et al. 2018; Pierozan et al. 2021), and quantify their shear strengths using miniature ball penetrometer (MBP) tests (Ads, Iskander, and Bless 2020a). MLPS was also used in physical laboratory-scale models of geotechnical systems that incorporated laser techniques and image processing to visualize failure surfaces developed upon loading caisson foundations (Wallace and Rutherford 2017).

A key characteristic of MLPS mixes that was identified early on is its significant thixotropic behavior. Such behavior is defined by Mitchell (1961) as a time-dependent change in strength common in highly sensitive clays and associated with a nonequilibrium state in interparticle forces after mixing, remolding, or compaction. The reversible, time-dependent strength gain represented by thixotropy has also been referred in the technical literature as aging, thixotropic hardening, and structuration (Mitchell 1961; Díaz-Rodríguez and Santamarina 1999). Mitchell and Soga (2005) reported two sources of shear strength gain for such materials: a fixed remolded strength (irreversible) and the thixotropic strength gain (reversible). Laponite mixtures can alternate between gel and liquid states after being left to age or after mixing, respectively. In fact, both sources of shear strength gain may be expected (i.e., the reversible and irreversible strength gains). Shahin and Joshi (2010) studied the aging dynamics of laponite with use of salt as additive. Although that study involved testing only one mixture with 2.8 % laponite concentration by weight at various salt concentrations, they conducted rheological tests that suggested an inherent irreversibility in the aging dynamics.

A practical limitation facing the use of laponite is the difficulty of preparing mixtures with high solid concentrations, partly because of the comparatively rapid gelation process. To address this issue, the use of additives has been adopted during sample preparation to retard the time of gelation upon mixing the MLPS powder with water (Mongondry, Nicolai, and Tassin 2004; Ruzicka and Zaccarelli 2011; Beemer et al. 2016). Specifically, sodium pyrophosphate (SPP) has been used in recent studies to facilitate the preparation of laponite mixtures at relatively high concentrations, producing mixtures of comparatively higher shear strength and stiffness (Ads, Iskander, and Bless 2020b; Ads et al. 2020). Laponite particles tend to aggregate after they overcome a certain energy barrier formed by the electrostatic repulsion that is caused by their negatively charged faces; so salt additive (e.g., SPP) results in a reduction of the energy barriers to delay aggregation of particles, thus facilitating preparation of mixtures at higher MLPS concentrations (Nicolai and Cocard 2001; Mongondry, Nicolai, and Tassin 2004). However, only a limited number of mixtures have been evaluated so far, so data are currently not available regarding the geotechnical properties of mixes prepared for ranges of laponite content, SPP dosages, and aging times that are relevant for physical models in geotechnical engineering. An understanding of the impact of SSP dosage on mix properties is particularly relevant given that this additive is key in facilitating the preparation of mixtures at comparatively high laponite contents. In summary, the current understanding and control of the impact of increasing SPP dosage on the geotechnical properties of laponite, while valuable, remain limited.

This paper presents the results of a comprehensive geotechnical testing program designed and executed to establish geotechnical properties of laponite that are relevant for geotechnical modeling using laponite as a clay simulant. The scope of the experimental program includes rheometer tests conducted to study the effect of thixotropy and irreversible reactions on the viscosity and strength of the laponite mixtures. Consistency/Atterberg limit tests were carried out to investigate the effect of the laponite content and aging time on the plastic and liquid limits of the mixes tested. Consolidation tests and undrained shear strength tests were conducted using a range of laponite mixtures.

Materials and Sample Preparation

MLPS is a synthetic layered silicate that exhibits transparency when mixed with water and has been used in a wide range of industrial applications (Thompson and Butterworth 1992). The specific product selected as the clay surrogate for this study is Laponite RD, which has also been referred to in the literature as laponite, produced by BYK Additives and Instruments. Laponite has a 2:1 layered silicate structure similar to that of the natural clay mineral hectorite (Van Olphen and Fripiat 1979; Pierozan et al. 2021). The laponite particles are disk-shaped with a thickness of 0.92 nm and an average diameter of 25 nm (BYK Additives and Instruments 2014). When compared with typical smectite clay particles, the laponite disks have a somewhat similar thickness but an average diameter that is about 40 times smaller. General properties and typical shear strength parameters of laponite, as reported in the available literature, are summarized in **Table 1**.

The undrained shear strength, S_u, reported in the table corresponds with values reported in several studies for different laponite contents, C_{lap}. The dosage of SPP used as rheological additive is also noted in the table as appropriate.

While laponite may provide a suitable analog to natural soft clays, it also presents several limitations and challenges: long consolidation times; very low density (i.e., high void ratio), and reported plasticity index values

TABLE 1
General laponite properties and strength parameters

Parameter	Value
Diameter[a], nm	25
Thickness[a], nm	0.92
Refractive index[a], %	1.5
Specific gravity[a], Gs	2.53
Plastic index[b], %	1,100
Liquid limit[b], %	1,280
$S_{u,\,L=4\,\%}$[c], kPa	0.3
$S_{u,\,L=4.5\,\%}$[c], kPa	0.4
$S_{u,\,L=9\,\%,\ SPP=0.405\,\%}$[d], kPa	1
$S_{u,\,L=13.5\,\%,\ SPP=1.992\,\%}$[d], kPa	1.6

Note: [a] BYK Additives and Instruments (2014); [b] El Howayek (2011); [c] Wallace and Rutherford (2015) at 7 days; [d] Ads, Iskander, and Bless (2020a) at 14 days.

that are even higher than those of bentonite (Beemer et al. 2016). To allow for the preparation of comparatively dense mixes (i.e., to increase the laponite content of the mixture), SPP has been used as an additive to provide additional time for entrapped air to escape before gelation ceases (Beemer et al. 2016). The SPP additive results in a mixture of reduced early strength that allows preparation of comparatively denser laponite mixtures. Without the addition of SPP, mixtures with relatively low laponite content (up to approximately 4.5 % by mass) are possible to obtain while still maintaining a negligible volume of entrapped air within the mixture. Increased C_{lap}, and consequently increased S_u, could be reached by adding SPP to distilled water to be used for preparation of the mixture. The mass percentages of SPP and laponite used during sample preparation are quantified as follows:

$$C_{\text{SPP}}(\%) = \frac{m_{\text{SPP}}}{m_w + m_{\text{SPP}} + m_{\text{lap}}} \times 100 \tag{1}$$

$$C_{\text{lap}}(\%) = \frac{m_{\text{lap}}}{m_w + m_{\text{SPP}} + m_{\text{lap}}} \times 100 \tag{2}$$

where C_{SPP} represents the dosage of the rheological additive; C_{lap} represents the laponite content; m_{SPP} represents the ovendry mass of SPP; m_{lap} represents the ovendry mass of laponite; and m_w represents the mass of distilled water. The amount of water that was added to prepare the mixtures, in order to achieve the total mass of water m_w, was defined considering the initial moisture content in SPP (68 %) and laponite (8.2 %).

As shown in **Table 1**, S_u of the various samples was reported to increase from 0.3 kPa for a laponite content (by mass) of 4 % to 1.6 kPa for a laponite content of 13.5 %, considering samples prepared using a SPP dosage of approximately 2 %. It should be noted that the maximum SPP dosage is limited by the solubility of the sodium additive in the type of water adopted for sample preparation (e.g., distilled, deionized, tap water), as solubility depends on the pH of the medium (Thompson and Butterworth 1992; Ads, Iskander, and Bless 2020a).

The laponite mixtures in this study were prepared following the mixture and timing protocols adopted by Pierozan et al. (2021), which are consistent with those proposed by BYK Additives and Instruments (2014). An overhead mixer was used to prepare all laponite samples in this testing campaign. A relatively high rate of rotation (2,200 rpm) was used to facilitate laponite hydration and mixture homogeneity. It should be noted that the chemicals were added to the solution in air-dry conditions, as indicated by equations (1) and (2). The batches of laponite slurry prepared in each stage had an average volume of 1.5 L, with mixing being conducted for approximately 10 min. Samples were placed in molds immediately after mixing to minimize the influence of aging. The slurry was poured into recipients or molds, depending on the laboratory tests to be carried out, for predefined aging periods (0.25, 1, 7, 14, and 28 days) at a constant laboratory air temperature (20°C). Individual samples were covered with a polyethylene plastic film to minimize desiccation and evaporation before testing. Note that preparation of mixtures with laponite content higher than 11 % was not feasible, as the maximum soluble amount of SPP in distilled water is around 3.2 % (Pierozan et al. 2021).

Viscosity Tests

Viscosity tests were conducted to determine the rheology and, eventually, possible sources of different strength gains occurring in laponite samples with time. In colloidal science, thixotropy is defined as an increase in viscosity under a state of rest (aging) and a decrease of viscosity when sheared/mixed/physically agitated (Mewis and Wagner 2009). In geotechnical engineering, and as mentioned in the "Introduction" section, thixotropy is thought of as a contributing parameter to strength gain for soft clays and, thus, colloidal suspensions behaving like clays. The evaluation of progressive thixotropic strength gain in this study involved quantifying the rheology (viscosity) of different laponite mixtures directly after mixing as well as after different aging periods. Therefore, when using laponite as transparent clay surrogate, the researcher should account for the thixotropic behavior of this material, which results in a time-dependent increase in stiffness and strength while at rest, as well as in softening upon remixing or remolding. The quantification of viscosity presented herein is complemented with the quantification of the time-dependent undrained shear strength that will be subsequently discussed in this paper.

The clay surrogate used in this testing program behaves as a non-Newtonian fluid (Mannheimer et al. 1989; Yi et al. 2018), the behavior of which can be assessed by characterizing the viscosity of the various mixtures and samples. In addition, quantifying the viscosity of laponite is expected to provide insight on the thixotropic strength gains that occur during aging. Finally, viscosity quantification after remixing of laponite samples will also facilitate the identification of different sources of shear strength.

RHEOMETER TESTING PROCEDURE

A Physica MCR 301 rheometer (see **fig. 1*A***) was used in this study to conduct tests under a constant rate ramp as well as a stress ramp, allowing measurement of the viscosity of the laponite samples. In an attempt to obtain the variation in viscosity at different shear rates, the adopted experimental procedure involved a controlled shear rate (CSR) mode of testing. While several methods can be adopted for the rheological measurements of fluids, a vane spindle (shown in **fig. 1*A***) was used in this study. This is because a vane spindle minimizes disturbances when penetrating the sample. Placing the sample on the lower spindle when using a plate spindle may considerably disturb the laponite sample, thereby erasing thixotropic strength gains that may have developed prior to testing. However, this does not mean that this option is the best in terms of uniform shear state.

Before initiating the CSR testing program, several trial tests were conducted on transparent clay surrogate mixtures to determine the appropriate time for the ramped rates in the CSR tests. The time selected for each strain rate is critical for obtaining proper viscosity results based on the residual strength obtained using an applied strain rate. The time to be adopted in the CSR tests can be determined by evaluating the variation of shear stress with time in a strain-controlled test. This evaluation was conducted for different strain levels (e.g., 0.1 s^{-1}, 100 s^{-1}). All tested samples showed trends reasonably similar to that shown in **figure 1*B***. The time history shown in this figure indicates that a duration of 20 s was adequate to reach the residual strength.

Accordingly, when performing the CSR tests, the adopted shear stress corresponds with that obtained at 20 s. The CSR tests were conducted using shear rates ranging from 0.01 s^{-1} to 500 s^{-1}. This range of strain rates represents soil failures that go from small/creep-like movements up to those associated with mass movements in slope failures.

SHEAR STRESS VARIATION WITH SHEAR RATE

Figure 2 shows the variation in recorded shear stress with increasing shear rates for laponite samples tested after different aging periods. The tests were conducted using different mixtures: L4-S0.00 (4 % laponite content, no SPP), L5-S0.06 (5 % laponite content, 0.06 % SPP dosage), L6-S0.06 (6 % laponite content, 0.06 % SPP dosage), and L8-S0.19 (8 % laponite content, 0.19 % SPP dosage). The results shown in **figure 2** are from tests conducted at

FIG. 1 Viscosity characterization of MLPS sample: (*A*) view of the rheometer device and (*B*) a CSR test results for a strain rate of 100 1/s.

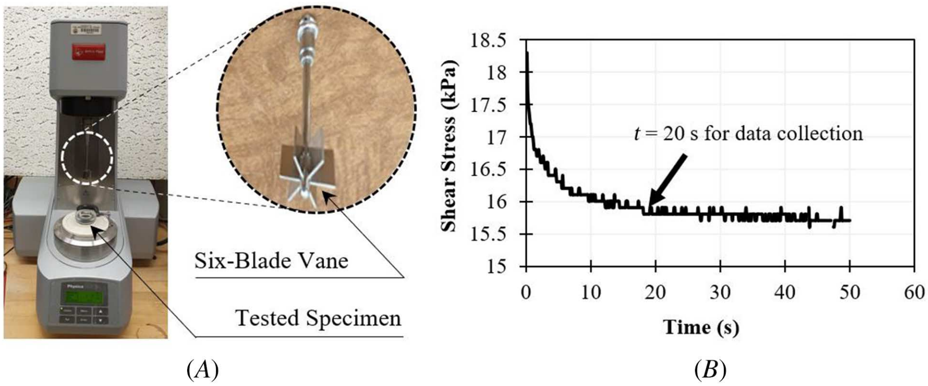
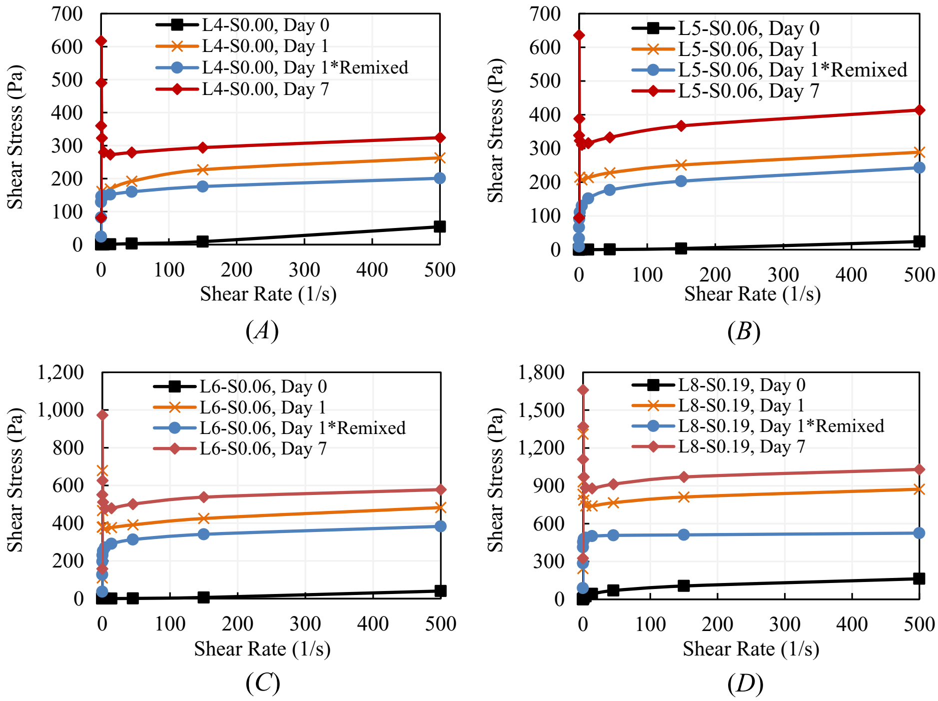


FIG. 2 Results of CSR tests showing shear stress as a function of the shear rate conducted for samples (*A*) L4-S0.00, (*B*) L5-S0.06, (*C*) L6-S0.06, and (*D*) L8-S0.19.



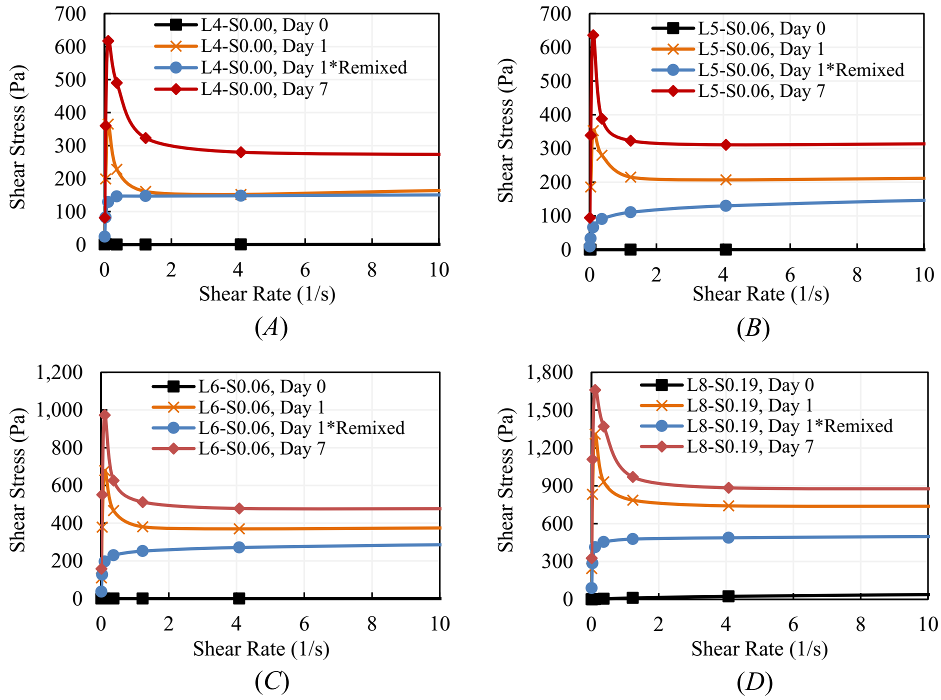
different aging periods using the following conditions for each mixture: (1) immediately after initial mixing; (2) 1 day after mixing; (3) immediately after remixing the same sample that had been aged for 1 day; and (4) 7 days after mixing. It should be noted that when direct testing after remixing is used, it means that around 1 min of rest is there, not more. The reason is that the rapid evolution that happens in such samples is in the orders of minutes. The 1-min time is between remixing the sample and retesting it. The remixing was performed using a thin tube that completely mixes the sample.

As expected, the shear stresses measured for all mixtures after 7 days of aging exceeded those obtained after 1 day of aging, which were in turn higher than the shear stresses measured immediately after mixing (Day 0). The shear stresses for the remixed sample (tested after 1 day of aging) were lower than those obtained using virgin samples (i.e., without remixing).

Inspection of the CSR test results obtained at comparatively low shear rates, namely below 10 s^{-1}, provides insight on the shear stress response of the different samples. This is mainly for samples that aged for at least 1 day because the freshly mixed samples hardly presented any strength at very low shear rates. **Figure 3** shows the previously discussed CSR test results for the different samples using a scale that facilitates visualization of the response under low shear rates.

The shear stress versus shear rate curves presented in **figure 3** show that the pattern of the remixed samples (aged for 1 day before remixing and testing) was clearly different from that of virgin mixtures (aged for 1 and 7 days before testing). This difference provides evidence of the aging and development of thixotropic behavior in such samples. Specifically, this behavior is consistent with that of sensitive clays, which present a well-defined peak strength and subsequent shear strength loss post the peak (Mitchell 1961). The trends in these results illustrate the loss of the thixotropic strength that had been gained upon remixing. Similar nonlinear trends in the shear stress versus shear rate response were reported by El Howayek (2011) for mixtures with comparatively low laponite content.

FIG. 3 Results of CSR tests showing shear stress obtained under comparatively low shear rates, as obtained for samples (*A*) L4-S0.00, (*B*) L5-S0.06, (*C*) L6-S0.06, and (*D*) L8-S0.19.



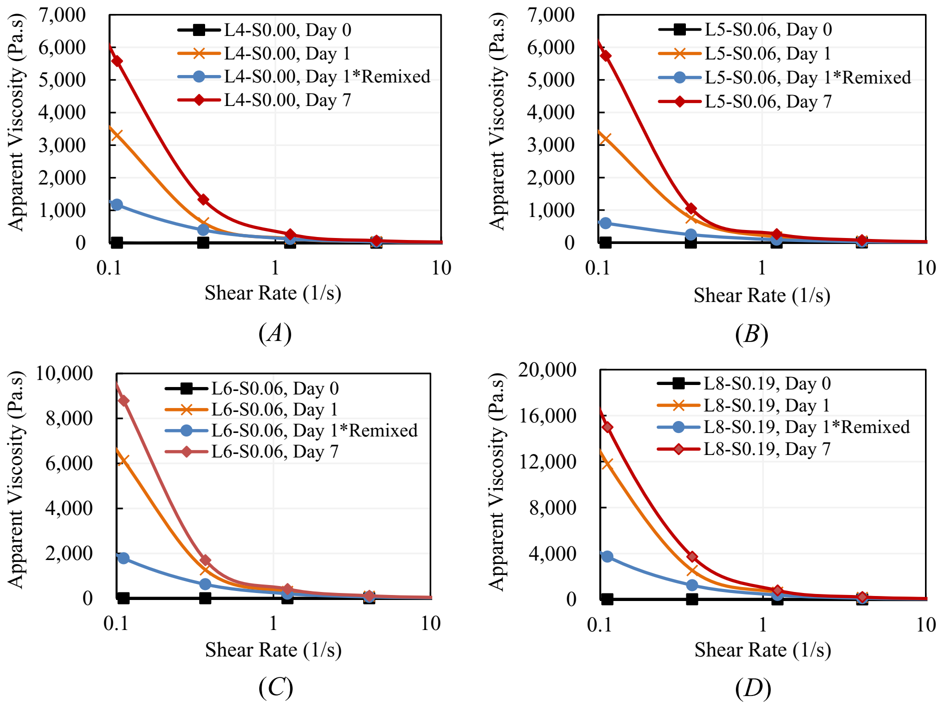
These results point to the presence of multiple contributions to the measured shear strength of laponite specimens. In fact, the stress of the specimen tested after remixing was higher than that of samples tested immediately after initial mixing (Day 0) but lower than that of mixtures tested after 1 day of aging (Day 1), indicating a source of strength that is irreversible (i.e., not lost after mixing). It should also be noted that results for fresh samples (Day 0) and samples tested directly after mixing (Day 1* remixed) present a non-Newtonian behavior because they were directly tested without allowing the buildup of thixotropic strength. Instead, the results obtained for other samples (Day 1 and Day 7) showed a non-Newtonian behavior, with an early peak at low shear rates because of the thixotropic strength gain after aging. These trends are consistent with the findings reported by Yi et al. (2018).

APPARENT VISCOSITY

The apparent viscosity, defined as the secant slope of the shear stress versus shear rate curve, was obtained from CSR tests for the different mixtures. The results are presented in figure 4 using a semilog scale for shear rates ranging from 0.1 s^{-1} to 10 s^{-1}. The apparent viscosity values obtained for strain rates ranging from 0.5 to 5 $s^{-1}$are comparable with those of very soft clays (Locat and Bergeron 1988).

The values of apparent viscosity increased significantly with increasing aging time, as illustrated by the results obtained for series Day 0, Day 1, and Day 7 for all four mixtures, reaching values of around 6,000 *Pa.s* for L4-S0.00 and L5-S0.06 (fig. 4*A* and 4*B*), which increase to 9,300 *Pa.s* and 16,500 *Pa.s* for samples L6-S0.06 and L8-S0.19, respectively (fig. 4*C* and 4*D*). A comparatively more viscous behavior is evident at low shear rates for aged mixtures as well as for remixed samples. Immediately after initial mixing, the apparent viscosity values for all mixtures became negligible, as shown in figure 4 for the Day 0 testing series. The results presented in figure 4 also show that the apparent viscosity converged when the shear rates exceeded approximately 2 s^{-1}.

FIG. 4 Apparent viscosity results for mixtures (*A*) L4-S0.00, (*B*) L5-S0.06, (*C*) L6-S0.06, and (*D*) L8-S0.19.

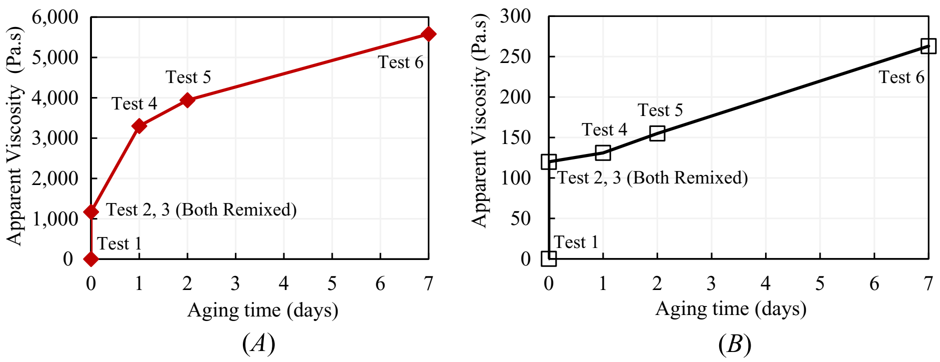


THIXOTROPY AND FIXED REMOLDED STRENGTH

The viscosity test results facilitated the evaluation of the potential sources of time-dependent strength gain (thixotropy) in addition to another source of irreversible strength gain. In colloidal science, suspensions that possess thixotropic strength gain could be linked with either chemical or physical irreversible strength that are separate from thixotropy and aging effects. For laponite samples, strong aggregation of particles occurs after mixing that was not removed after mechanical agitation and shearing (as shown in the previous section). Figure 5 presents the apparent viscosity results, which may be considered an indicator of the strength gain, as a function of aging time for two selected strain rates ($\dot{\varepsilon} = 0.1\, s^{-1}$ and $\dot{\varepsilon} = 1\, s^{-1}$).

The results shown in figure 5*A* and 5*B* correspond to six tests conducted using mixture L4-S0.00 and tested at different aging times and under different conditions (fresh, aged, or remixed). As shown in figure 5*A*, Test 1

FIG. 5 Apparent viscosity as a function of aging period for shear rates of (*A*) 0.1 1/s and (*B*) 1.0 1/s.



that corresponds to time = 0 yielded a negligible apparent viscosity, as it corresponds to a fresh sample tested directly after mixing. The second point plotted on the *y*-axis with an apparent viscosity of 1,170 *Pa.s* represents the two overlaying results corresponding to Tests 2 and 3. These two tests correspond to Day 1 remixed and Day 2 remixed samples, corresponding to samples that were allowed to age for 1 and 2 days, remixed, and then tested directly. Tests 4, 5, and 6 correspond to samples aged for 1, 2, and 7 days and tested without any remixing, resulting in apparent viscosity values of 3,300, 3,940, and 5,580 *Pa.s*, respectively. These results indicate that: (1) fresh mixes have low apparent viscosity compared with aged samples; (2) aging time leads to a significant increase in apparent viscosity; and (3) after an aging period of 1 day, remixed samples yield a constant apparent viscosity. These observations are also consistent with the results presented in **figure 5*B***, which represent the variation of apparent viscosity with aging time but obtained considering a different strain rate, $\dot{\varepsilon} = 1\,s^{-1}$.

Overall, the results in **figure 5*A*** and **5*B*** clearly show the thixotropic strength gains in Tests 4, 5, and 6, which recorded an increase in the apparent viscosity while at rest and after initial mixing/remixing. This is true for repetitive cycles of mixing and remixing, which is clearly stated by researchers in the past decades when defining thixotropic strength gain. However, in addition to the thixotropic strength component shown at different strain rates, an additional strength gain was detected, which contributed to the increase in apparent viscosity in Tests 2 and 3. This strength gain could be thought of as a structural strength gain from strong aggregation of particles (Mewis and Wagner 2009) because it ceased after Day 1 and was not erased by remixing, so it represents a nonreversible strength gain. The findings from this section are consistent with information presented by Mitchell and Soga (2005), who reported two sources of strength gain for soils that show thixotropic behavior: a reversible component (thixotropy) and a nonreversible strength component.

Atterberg Limits

In this section, the plastic and liquid limits of laponite mixtures were determined for samples prepared using different laponite contents and SPP dosages. Specifically, tests were conducted using the 30 mixtures listed in **Table 2** (with varying laponite and SPP dosages).

PLASTIC LIMIT

The conventional method reported by ASTM D4318-10, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils* (Withdrawn/Superseded), (hand rolling) was used to determine the plastic limit of laponite. The plastic limit obtained for laponite mixtures prepared without the addition of SPP was $PL = 200\%$. This result is consistent with values reported by Wallace and Rutherford (2015).

The PL value obtained for laponite exceeds that of typical montmorillonite and bentonite clays (e.g., $PL_{\text{montmorillonite}} = 75\%; PL_{\text{bentonite}} = 100\%$). The effect of SPP on the plastic limit was explored by testing mixes aged for 7 days and prepared at different laponite contents and SPP dosages. However, in order to conduct the testing for plastic limit at different water contents, the mixtures should have an initial condition that allows the hand rolling involved in the testing procedure. This was achieved by subjecting the samples to cycles of oven-drying and wetting until reaching adequate workability. Surprisingly, the range of obtained plastic limit values showed a comparatively narrow range of values, ranging from 180 to 230 % regardless of the SPP dosage and drying/wetting cycles that were done with/without aging.

LIQUID LIMIT

The conventional Casagrande approach, as documented in the liquid limit method corresponding to ASTM D4318-10, was followed to determine the liquid limit, LL, of the different laponite mixes. The liquid limit measured after an aging time of 1 day after mixing and without the use of SPP was $LL = 1{,}200\%$, which corresponds to a laponite content of 8 %. The plasticity index is thus $PI = 1{,}000$, consistent with a plastic limit determined previously as $PL = 200\%$. This is also consistent with previously reported values (e.g., Chini et al. 2015), resulting in a classification of “high plastic inorganic clays” according to the USCS.

TABLE 2
Plastic limit for different laponite mixtures

Mixture	Laponite, %	SPP %	PL %
L2-S0.00	2	0	210
L3-S0.00	3	0	207
L3-S0.03	3	0.03	195
L3-S0.06	3	0.06	198
L3-S1.77	3	1.77	185
L4-S0.00	4	0	205
L4-S0.03	4	0.03	196
L4-S00.6	4	0.06	202
L4-S0.44	4	0.44	192
L4-S0.88	4	0.88	221
L5-S0.00	5	0	204
L5-S0.06	5	0.06	213
L5-S0.43	5	0.43	215
L5-S1.71	5	1.71	200
L5-S3.32	5	3.32	197
L6-S0.00	6	0	230
L6-S0.06	6	0.06	214
L6-S0.43	6	0.43	220
L6-S1.69	6	1.69	208
L6-S3.28	6	3.28	186
L8-S0.00	8	0	200
L8-S0.10	8	0.1	203
L8-S0.43	8	0.43	220
L8-S1.65	8	1.65	210
L8-S3.21	8	3.21	188
L9-S0.42	10	0.42	223
L11-S0.10	11	0.1	212
L11-S0.41	11	0.41	210
L11-S1.58	11	1.58	190
L11-S3.07	11	3.07	194

The liquid limit tests were conducted 1 day after mixing, considering that laponite has negligible shear strength immediately after mixing. Some preliminary trial tests were also conducted using samples after aging for 1, 2, 4, 6, 8, and 12 h. The variability of the liquid limit test results was found to decrease significantly with increasing aging time before conducting the liquid limit test. Specifically, the liquid limit values obtained after 6 h of aging were found to be particularly consistent.

The effect of laponite content, SPP, and aging time on the liquid limit was investigated using the sample mixtures mentioned in Table 3. Samples were left to age in Casagrande cups while remaining sealed with Saran Wrap to avoid water losses during aging. Samples were left to age for a period of 28 days at a temperature of 25°C. Mixtures with a laponite content below 8 % were in a liquid state after initial mixing, with the number of blow counts (to close the initial groove by 13 mm) in the Casagrande apparatus below 15 even after the comparatively long aging period (28 days). Table 3 summarizes the results obtained using the Casagrande apparatus.

The results indicate that increasing laponite content (for a given SPP dosage) leads to increasing energy (i.e., higher number of blows) needed to close the groove over a length of 13 mm. This trend can be observed by comparing the results obtained for mixtures L8-S0.43, L9-S0.42, and L11-S0.41 (Table 3). These samples have essentially the same SPP concentration and were aged over same period of time; yet, the number of blows showed a clear increase with increasing laponite content.

TABLE 3

Number of blows obtained using Casagrande liquid apparatus for different laponite mixtures to close 13-mm groove

			Number of Blows			
Mixture	Lap, %	SPP, %	1 Day	7 Days	14 Days	28 Days
L2-S0.00	2	0.00	0	0	0	0
L3-S0.00	3	0.00	0	0	0	0
L3-S0.03	3	0.03	0	1	1	1
L3-S0.06	3	0.06	0	1	1	1
L3-S1.77	3	1.77	0	0	0	0
L4-S0.00	4	0.00	2	4	4	5
L4-S0.03	4	0.03	1	1	1	1
L4-S00.6	4	0.06	0	1	2	2
L4-S0.88	4	0.88	0	0	0	0
L4-S0.44	4	0.44	0	0	0	0
L5-S0.00	5	0.00	4	6	7	9
L5-S0.06	5	0.06	2	3	3	5
L5-S0.43	5	0.43	0	0	0	0
L5-S1.71	5	1.71	0	0	0	0
L5-S3.32	5	3.32	0	0	0	0
L6-S0.00	6	0	10	12	12	13
L6-S0.06	6	0.06	4	5	6	6
L6-S0.43	6	0.43	0	1	1	2
L6-S1.69	6	1.69	0	0	0	0
L6-S3.28	6	3.28	0	0	0	0
L8-S0.00	8	0	25	28	30	32
L8-S0.10	8	0.10	14	16	20	22
L8-S0.43	8	0.43	7	10	11	14
L8-S1.65	8	1.65	0	1	2	2
L8-S3.21	8	3.21	0	0	0	0
L9-S0.42	10	0.42	14	15	17	18
L11-S0.10	11	0.1	35	36	40	43
L11-S0.41	11	0.41	24	27	27	30
L11-S1.58	11	1.58	12	15	17	19
L11-S3.07	11	3.07	6	9	12	14

As for the effect of SPP, it decreases the number of blows needed to close the 13-mm groove as the SPP content increases because SPP, as mentioned earlier, retards gelation. For example, this trend can be observed when comparing the five samples with laponite content of 8 % (i.e., L8-S0.00, L8-S0.10, L8-S0.43, L8-S1.65, and L8-S3.21), which shows that an increasing SPP dosage led to a decreasing blow count.

Finally, the effect of aging time, illustrated by inspecting the results of sample L8-S0.43, the number of blows increased from 7 to 14 as aging time increased from 1 to 28 days. This is also shown in almost all the other mixes.

Consolidation Tests

The rate and magnitude of laponite consolidation in response to axial loading was determined in this study by conducting a series of consolidation tests on different mixtures prepared with and without using SPP as additive. **Table 4** summarizes the characteristics and initial conditions of the mixtures used in the consolidation testing program. The tests were conducted using samples aged for 7 days, which had been sealed using Saran Wrap to minimize evaporation and thus maintaining their initial water content. All five samples were left to age inside the oedometers.

TABLE 4

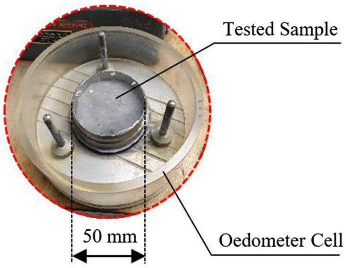
Characteristics and initial conditions of the mixtures used for 1-D consolidation testing

Mix	Laponite, %	SPP, %	w_0, %	e_0
L4-S0.00	4	0	2,400	60.72
L5-S0.06	5	0.06	1,900	48.07
L6-S0.06	6	0.06	1,567	39.64
L8-S0.10	8	0.10	1,150	29.10
L11-S0.41	11	0.41	733	18.55

Note: e_0 = initial void ratio; w_0 = initial water content.

FIG. 6

View of the specimen prepared with mixture L4-S0.00 ready for 1-D consolidation testing.



The initial water content of each specimen was measured by oven-drying a sample of the relevant mixture prior to consolidation. The void ratio of the samples was obtained by assuming that the clay surrogate had reached full saturation after 7 days of aging and adopting a laponite specific gravity of 2.53 as reported by Chini et al. (2015).

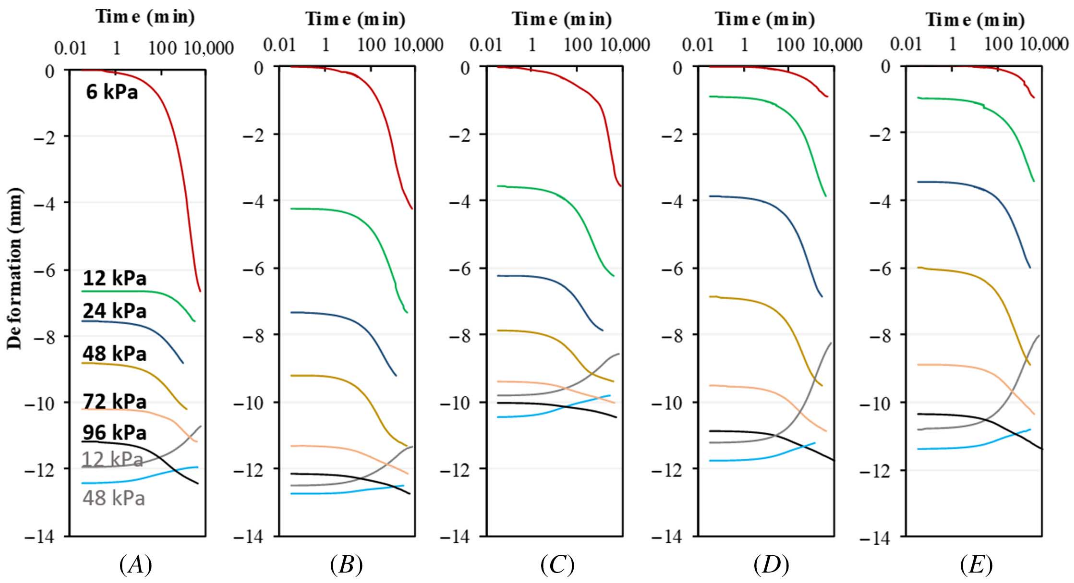
The initial void ratio values of the different mixtures are significantly higher than those of typical natural clays. The specimens were prepared with a diameter of 62.5 mm and a height of 25.4 mm. **Figure 6** shows a view of the specimen prepared with mixture L4-S0.00 after being placed in the oedometer and prior to the initial stage of consolidation testing.

TYPICAL CONSOLIDATION CURVES

The consolidation results obtained for five one-dimensional (1-D) consolidation tests conducted as part of this study are presented in **figure 7**. The curves for both loading and unloading stages show trends that are consistent with those typically obtained for natural clays. The average duration of the load increments needed to reach the end of primary consolidation and was approximately 3 days. Consequently, the total duration of each consolidation test, including the various loading and unloading stages, ranged from 3 to 4 weeks. The loading phase involved six load increments with normal stresses of 6 kPa, 12 kPa, 24 kPa, 48 kPa, 72 kPa, and 96 kPa while the unloading stages were conducted under normal stresses of 48 kPa and 12 kPa.

At the end of primary consolidation, the volume reduction of the different samples ranged from 60 to 70 %, regardless of the initial laponite content and SPP dosage used in the mix. The vertical displacement obtained for samples with low laponite contents (**fig. 7*A*** and **7*B***) showed a marked reduction in volume even for the low applied stresses, whereas samples with high laponite contents (**fig. 7*D*** and **7*E***) showed comparatively small deformations under low applied stresses and only showed significant levels of displacements in the higher range of normal stresses applied. The initial 6-kPa loading stress level for samples with 8 % and 11 % laponite contents (**fig. 7*D*** and **7*E***) served more like a seating stage rather than a loading stage. This could be related to the increased stiffness of specimens with higher laponite content. This trend highlights the importance of using low load

FIG. 7 Loading and unloading consolidation curves for mixtures (*A*) L4-S0.00, (*B*) L5-S0.06, (*C*) L6-S0.06, (*D*) L8-S0.10, and (*E*) L11-S0.41.



stresses for mixtures with low laponite content (e.g., 4 %), consistent with recommendations by Wallace and Rutherford (2015). However, for the experiments to be comparable, similar load increments were adopted in each of the tests carried out in this study.

As the loading stress levels increased, all samples showed remarkable deformation. The highest normal stress applied on all samples was 96 kPa, which exceeds the stress level of normal stresses in laponite tests reported in the literature (e.g., Wallace and Rutherford 2015). The samples were unloaded in two stages during the unloading phases of testing. The first stage involved decreasing the applied stresses from 96 to 48 kPa. During this stage, swelling for all tested mixtures ranged only from 0.5 to 0.8 mm. However, during the second unloading stage to 12 kPa, more pronounced swelling was observed in all samples, with measured vertical displacements ranging from 1.0 to 2.3 mm.

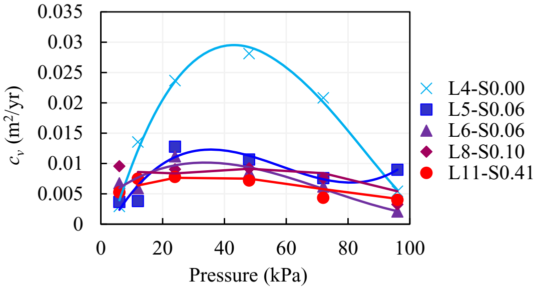
It should be noted that the tests conducted in this study reached reductions in volume as high as 70 %. This corresponds to achieving final laponite contents of 10.3 % and 21 % after loading samples with initial laponite content of 4 % and 11 %, respectively. As previously indicated, the maximum laponite content that could be achieved by mixing from slurry with the maximum soluble SPP dosage was below 15 %. Accordingly, high laponite content samples (up to 21 %) could be achieved by consolidation strategies after initial sample mixing.

An important thing to note here is the partial loss in transparency of the mixtures, where the mixtures became more translucent at the end of the consolidation tests compared with the initial level of transparency before consolidation. The level of transparency lost was not determined or assessed by this study; however, for future testing, researchers should be aware of possible transparency losses when conducting model tests if they were to consolidate the samples prior to testing.

COEFFICIENT OF CONSOLIDATION

The coefficient of consolidation, c_v, of laponite mixtures was calculated using the Casagrande and Fadum (1940) t_{50} method for each compression stage corresponding to the different vertical stresses, and the variation of c_v with the vertical applied stress is shown in figure 8. The results show an initial trend in which c_v either increases with increasing applied stress or remains constant, followed by a decreasing trend beyond approximately 48 kPa,

FIG. 8 Variation in the coefficient of consolidation with effective vertical pressure for 1-D consolidation samples with MLPS content ranging from 4 to 11 % and varying SPP dosages.



during which c_v decreases with increasing effective vertical stresses. The observed trend is consistent with that reported by Duncan (1993) and Elkateb (2018), who reported various shapes for the coefficient of consolidation curves of natural clays with applied effective pressure.

The results also show a clear decrease in c_v with increasing initial laponite content (from 4 % up to 11 %). The decrease in coefficient of consolidation was significant when increasing the laponite content from 4 % to 5 %, unlike the case when increasing the laponite content from 5 % to even 11 %. This drop is because of the change in soil hydraulic conductivity (k) and compressibility (m_v). However, the c_v values remained essentially unchanged for higher values of laponite content (ranging from 5 to 11 %).

The mixture L4-S0.00 resulted in the highest c_v, at 48 kPa with a value of 0.028 m^2/yr, which is comparable with that of bentonite at 50-kPa confinement and 20 % bentonite content (Chenari et al. 2018). Thus, c_v values of a sample with an initial laponite content of 4 % can be considered consistent with those of a sample with a 20 % bentonite content.

COMPRESSIBILITY CURVES

Figure 9 shows the compressibility curves (i.e., the void ratio at the end of primary consolidation as a function of the applied effective vertical stresses) as obtained from the different stages during the consolidation tests (both compression and swelling stages). The initial void ratio of the five mixtures tested (e_0 ranging from 18 to 60) was considerably higher than that of bentonite clay (e_0 ranging from 0.5 to 2.0). This is true because of the high water content used during sample preparation of laponite mixtures (**Table 4**).

In spite of the decrease in void ratio observed after consolidation testing for the different laponite specimens, the final void ratio achieved after testing can still be considered comparatively high. For example, the sample with the densest initial mixture (L11-S0.41) showed a decrease in void ratio from 18.55 to 6.67 at the end of the primary

FIG. 9

Compressibility curve for five mixtures after 1-D consolidation testing.

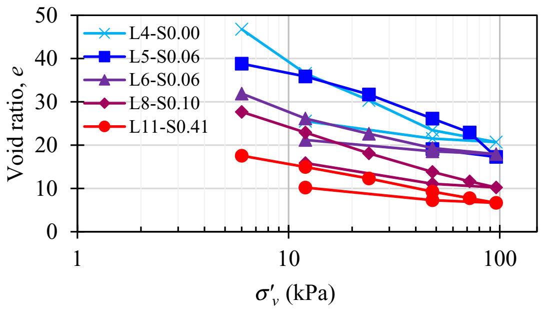


TABLE 5
Compression and swelling indexes for the different 1-D consolidation tests conducted

	Test					
	L4-S0.00[a]	L4-S0.00	L5-S0.06	L6-S0.06	L8-S0.10	L11-S0.41
Cc	16.60	16.63	13.95	9.10	9.65	9.34
Cs	6.30	6.05	5.27	4.49	4.61	3.91

Note: [a] Wallace and Rutherford (2015).

consolidation stage. **Table 5** summarizes the variation in the compression and swelling indexes, C_c and C_s, respectively, for all tests. Both indexes show a decreasing trend with increasing laponite content. The values of C_c and C_s for the L4-S0.00 mixture are consistent with those reported by Wallace and Rutherford (2015).

The compression and swelling indexes were found to decrease with increasing laponite content, as depicted by the decreasing slope of curves in **figure 9** with increasing laponite content. However, the ratio between the initial and final void ratios in all tests was reasonably constant and equal to approximately 3. This can be justified by the similar degree of vertical deformation that was measured in the different consolidation tests. For instance, the mixture L4-S0.00 showed an initial void ratio of around 60 before loading, reaching a final void ratio of roughly 22 after the last loading increment (i.e., a ratio of initial to final void ratio of about 3). Similarly for mixture L11-S0.41, the void ratio decreased from 18.6 to 6.5 after the final loading increment. It should be noted that none of the tested mixtures showed any evidence of a break in the reasonably linear trend in a semilog space, which could represent a pre-consolidation pressure.

A relevant observation that could be drawn from the consolidation test results conducted in this study is that the use of SPP additive did not hinder the consolidation of the different laponite mixtures. Additional insight could be gained by evaluating the effect of SPP dosage on the level of consolidation and consolidation parameters for a given laponite content. However, it was evident that for all five samples tested (with and without SPP), a reasonably consistent final level of vertical deformation of around 60–70 % was achieved (see **fig. 7**). Consequently, for a given laponite content, the SPP dosage appears to not have a significant impact on the consolidation results.

Undrained Shear Strength

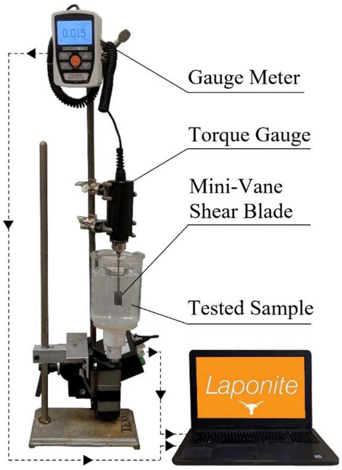
A tailored vane shear test device was designed and constructed in this project to determine the undrained shear strength of different laponite mixtures. An experimental testing program was subsequently conceived and executed to evaluate the effects of laponite content, aging time, SPP dosage, storage temperature, and remixing on the undrained shear strength of laponite.

The vane blade adopted in this study was selected considering the range of particularly low expected shear strength values. The blade measured 25.4 mm in height, 12.52 mm in diameter, and 0.762 mm in thickness. A stepper motor (Oriental Motors, model ARM46AC-T10) was used to rotate the vane and shear the laponite mixtures at a constant speed of 1 rad/min (~60°/min), as recommended by ASTM D4648/D4648M-13, *Standard Test Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil* (Withdrawn/Superseded). A gauge (Mark-10, model MTT03-10Z) with a capacity of 0.07 N.m was used to control the torque during testing. A leveling table was used to lift the sample to the required position to minimize sample disturbance. Readings were taken at a depth of 60 mm (approximately 5 times the blade diameter) below the sample surface, which is consistent with the minimum depth of one blade diameter specified in ASTM D4648/D4648M-13. A displacement of 1 radian was selected as the reference for all tests. **Figure 10** depicts the vane shear setup developed in this investigation.

The laponite content (by dry mass) of the samples tested in this experimental program ranged from 2 to 11 %, whereas the additive dosage ranged from 0.00 to 3.30 %. The various mixtures and samples were prepared

FIG. 10

Vane shear setup used for determination of undrained shear strength of different MLPS mixes.



following the mixing protocols described by Pierozan et al (2021). After mixing, each batch of laponite slurry was poured into a 600-mL beaker with an internal diameter meeting the free border requirements specified in ASTM D4648/D4648M-13 to minimize boundary effects. The mixtures were subsequently covered with Saran Wrap to avoid desiccation and were left to age for predetermined periods of time (1, 7, 14, and 28 days).

EFFECT OF LAPONITE CONTENT

A series of laboratory vane shear tests were conducted on 30 transparent clay mixtures involving varying laponite contents and SPP dosages. The laponite content ranged from 2 to 11 %, which corresponds to a range of laponite contents that are well beyond those previously reported in the technical literature. The percentage of dry SPP used in the testing program ranged from 0 to 3.3 %. Distilled water was used in all the mixtures prepared in this study. It should be noted that the maximum soluble concentration of SPP in distilled water is 3.30 %. For each mixture, four identical samples were prepared in separate molds for testing after aging for 1, 7, 14, and 28 days under a constant temperature of 25°C.

Table 6 provides a summary of the peak S_u values obtained for the 120 shear strength tests conducted as part of this study. Previously reported studies (e.g., Wallace and Rutherford 2015) had involved tests conducted using mixtures prepared with laponite content values of 4 % and 4.5 % without the addition of SPP, which ultimately resulted in a peak strength of around 0.5 kPa. Results from shear strength tests carried out in this study and summarized in **Table 6** show peak S_u values often exceeding 1 kPa and reaching up to 2 kPa for mixtures with comparatively high laponite content achieved by using SPP additive. These comparatively high S_u values were obtained as early as after 7 days of aging (e.g., mixtures L9-S0.42, L11-S0.10, L11-S0.41, and L11-S1.58). The effect of one of the relevant variables, laponite content, was quantified by comparing the S_u results obtained at a constant temperature (i.e., 25°C, the same aging period, and similar ranges of SPP dosage. The results of the comparison are presented in **figure 11** and indicate that the S_u shows an increasing trend with increasing laponite content for a given aging period and SPP dosage.

The results in **figure 11*A*** correspond to the undrained shear strength S_u of laponite mixtures prepared without SPP additive (i.e., 0 % SPP content). They show a clear increase in S_u with increasing laponite content. For example, the results for an aging period of 1 day indicate that the S_u approximately doubles for every 1 % increase in laponite content. Similarly increasing trends can also be observed in this figure for aging periods of 7, 14, and 28 days.

Increasing trends in S_u similar to those obtained without SPP additive can also be observed with increasing laponite content for the various ranges of SPP dosage considered in this study, as observed in **figure 11*B*–*E***. In these cases, S_u also approximately doubles for every 1 % percent increase in laponite content.

TABLE 6
Undrained shear strength for 30 mixtures over time

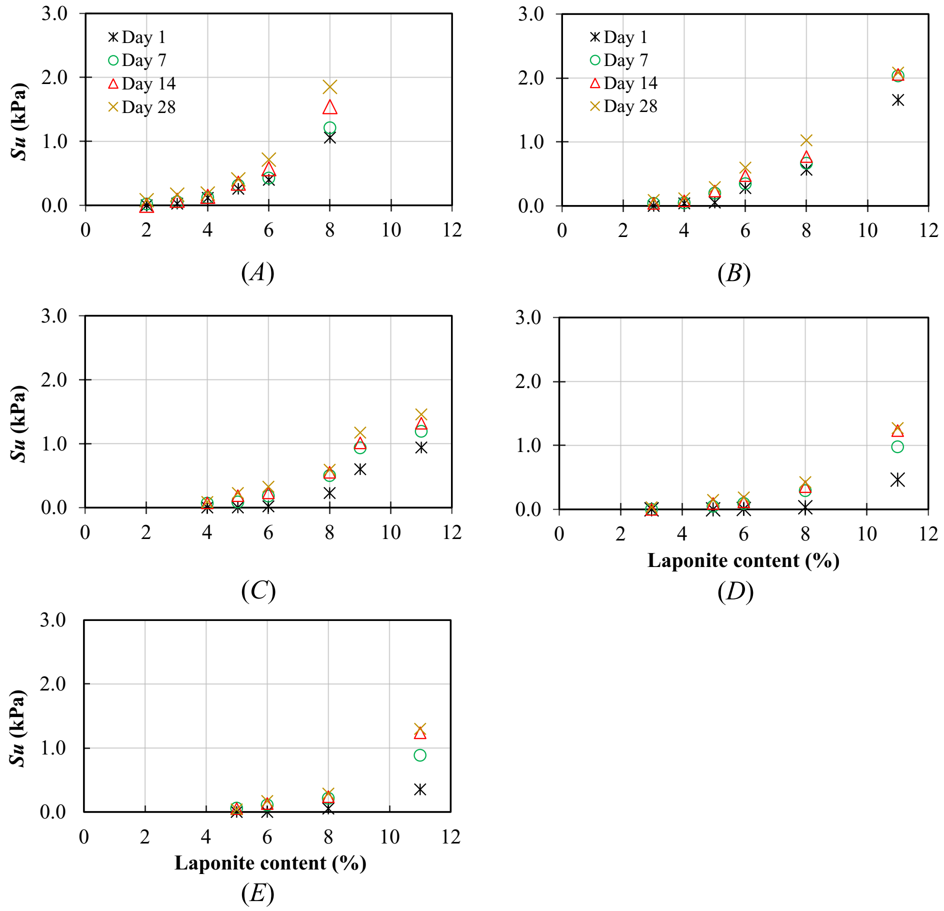
			S_u, kPa			
Mix Label	C_{lap}, %	C_{SPP}, %	1 Day	7 Days	14 Days	28 Days
L2-S0.00	2	0.00	0.001	0.001	0.001	0.080
L3-S0.00	3	0.00	0.027	0.053	0.080	0.166
L3-S0.03	3	0.03	0.001	0.047	0.040	0.107
L3-S0.06	3	0.06	0.001	0.040	0.040	0.093
L3-S1.77	3	1.77	0.001	0.001	0.001	0.033
L4-S0.00	4	0.00	0.117	0.120	0.150	0.185
L4-S0.03	4	0.03	0.060	0.080	0.100	0.110
L4-S00.6	4	0.06	0.040	0.047	0.080	0.120
L4-S0.44	4	0.44	0.001	0.067	0.073	0.087
L4-S0.88	4	0.88	0.001	0.040	0.027	0.087
L5-S0.00	5	0.00	0.260	0.313	0.346	0.405
L5-S0.06	5	0.06	0.053	0.200	0.233	0.295
L5-S0.43	5	0.43	0.001	0.087	0.186	0.226
L5-S1.71	5	1.71	0.001	0.047	0.093	0.147
L5-S3.32	5	3.32	0.001	0.060	0.053	0.040
L6-S0.00	6	0	0.400	0.426	0.573	0.715
L6-S0.06	6	0.06	0.280	0.346	0.475	0.599
L6-S0.43	6	0.43	0.020	0.180	0.229	0.326
L6-S1.69	6	1.69	0.007	0.093	0.120	0.186
L6-S3.28	6	3.28	0.001	0.107	0.132	0.172
L8-S0.00	8	0	1.059	1.212	1.542	1.851
L8-S0.10	8	0.10	0.566	0.666	0.773	1.026
L8-S0.43	8	0.43	0.226	0.499	0.553	0.592
L8-S1.65	8	1.65	0.033	0.293	0.355	0.425
L8-S3.21	8	3.21	0.053	0.213	0.240	0.288
L9-S0.42	9	0.42	0.599	0.932	1.012	1.172
L11-S0.10	11	0.1	1.658	2.031	2.056	2.084
L11-S0.41	11	0.41	0.939	1.192	1.319	1.456
L11-S1.58	11	1.58	0.466	0.979	1.232	1.272
L11-S3.07	11	3.07	0.353	0.886	1.239	1.300

The impact on S_u with increasing laponite content is consistent with results reported by Mourchid and Levitz (1998) regarding the effect of gelation on the strength of soft clay surrogates. However, as shown by the results presented in **figure 11**, the rate of increase of S_u with laponite content cannot be described by a single variable, as the S_u depends on aspects such as SPP dosage and aging time.

Overall, S_u results obtained in this study show that the rate of shear strength increase is not constant and varies with additive concentration. The results obtained in this study indicate that mixtures with laponite content exceeding 8 % could not be prepared without the SPP additive and that mixtures with increasing laponite content were achievable with increasing SPP dosage. However, adding SPP resulted in a detrimental decrease in S_u for a given laponite content, as discussed further in the next section of this paper.

What is also important from these results is that they compare well with previous undrained shear strength studies on laponite samples with similar concentrations and testing conditions. Ads, Iskander, and Bless (2020a) conducted undrained shear strength tests on samples with 4.5 %, 9 %, and 13.5 % laponite content and 0 %, 0.405 %, and 1.992 % SPP dosages, respectively. The authors used MBP tests to detect the S_u variation at different aging times and at different depths. Results from the testing campaign in this paper are comparable with the results in Ads, Iskander, and Bless (2020a), where the S_u results for the samples L5-S0.00 and L9-S0.43 in this

FIG. 11 Undrained shear strength for increasing MLPS content after different aging periods for SPP dosages of (*A*) 0 %, (*B*) 0.05–0.10 %, (*C*) 0.40–0.50 %, (*D*) 1.6–1.8 %, and (*E*) 3.0–3.3 %.



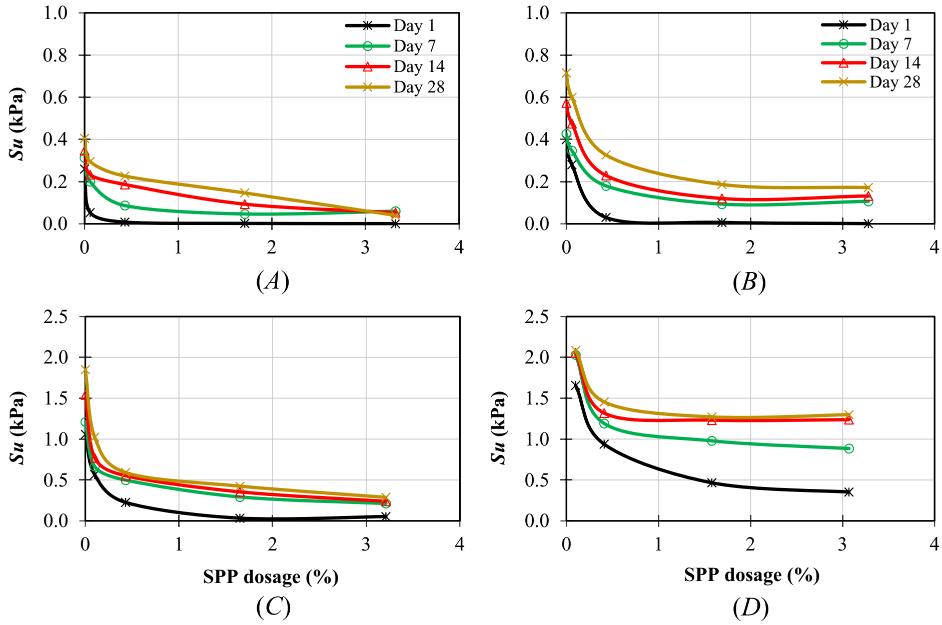
research compared very well with samples with 4.5 % laponite content and 0 % SPP and 9 % laponite content and 0.405 % SPP, respectively.

EFFECT OF SPP DOSAGE

To better understand the effect of SPP dosage on the undrained shear strength of laponite mixtures, an evaluation was conducted by keeping constant other variables (e.g., laponite content, aging time, temperature) that also affect the S_u of laponite. The results presented in Table 6 and figure 11 indicate that S_u decreases with increasing SPP dosage for a given laponite content. For example, through referring to the results in Table 6, the S_u reached after 28 days of aging without SPP additive is 1.85 kPa for a laponite content of 8 % (also see fig. 11*A*); however, for the same aging period and laponite content, the S_u achieved is only 0.29 kPa when using an SPP dosage of 3.2 % (see fig. 11*E*). The use of SPP decreases the rate of gelation, making the sample less viscous, which in turn helps explain the decreased S_u obtained with increasing SPP dosage at any given aging period. Figure 12 shows the effect of SPP dosage on S_u or mixtures prepared using different values of laponite content and aging periods.

The results in figure 12*A* for a laponite content of 5 % and aging period of 1 day show a rapid decrease in S_u with increasing SPP dosage. For this laponite content and aging period, the results show that the most significant drop in shear strength occurs for comparatively low SPP dosages (e.g., SPP < 0.5 %).

FIG. 12 Undrained shear strength variation with SPP dosage at different aging times for MLPS contents of (*A*) 5 %; (*B*) 6 %; (*C*) 8 %, and (*D*) 11 %.



Specifically, as shown in figure 12*A*, S_u for Day 1 dropped about 99 % for an increase in SPP dosage from 0 to about 0.5 %, with the drop reaching about 100 % for an SPP dosage of 1.7 %. For aging times of 7, 14, and 28 days, the reduction in strength because of the use of SPP is about 75 % for an SPP dosage of 1.7 %, reaching a reduction of about 85 % when the SPP dosage increased to 3.3 %. The behavior observed in figures 12*B* and 13*C* for laponite contents of 6 % and 8 % for the different aging periods is similar to that observed in figure 12*A* for a laponite content of 5 %.

While the reductions in S_u with increasing SPP dosage showed similar trends for laponite contents below 8 %, the trends were somewhat different for results obtained using a laponite content of 11 %, as shown in figure 12*D*. As shown in this figure, the results for Day 1 show reductions in S_u of 70 % for a SPP dosage increasing from 0 to 1.7 %. This reduction in strength is not as significant as the strength reduction observed for Day 1 for lower laponite concentrations and similar ranges of SPP dosage (see fig. 12*A*–*C*). Similarly, the results for Days 7, 14, and 28 show average reductions in strength of 35 % and 40 % for increases in SPP dosage to 1.7 % and 3.3 %, respectively. In this case, the shear strength loss obtained in mixtures with a laponite content of 11 % is also significantly lower than the reductions (ranging from 75 to 85 %) obtained when using lower laponite contents.

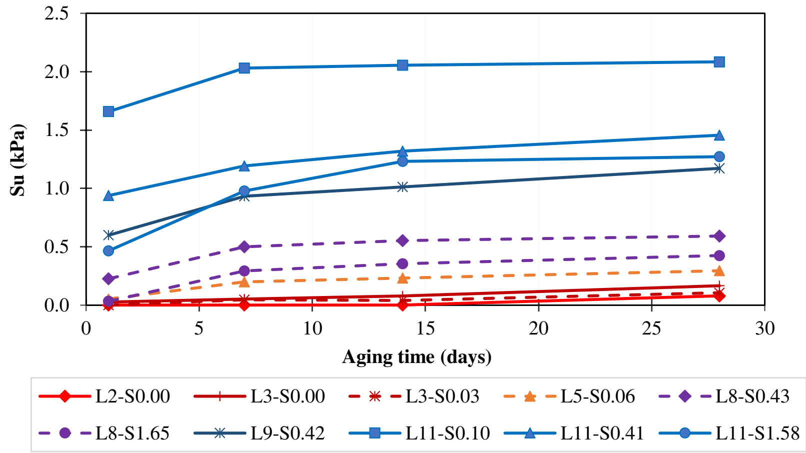
It should also be noted that the rate of shear strength decrease becomes less significant with increasing aging periods, showing the highest rate of shear strength drop at early aging times and the lowest rate of shear strength decrease for an aging period of 28 days. This trend is further discussed in the next section of the paper.

EFFECT OF AGING TIME

The effect of aging time on S_u of laponite mixtures can be observed in figure 13, where the variation of S_u as a function of the aging time for 10 laponite mixtures is presented. The mixtures shown in figure 13 are representative of the behavior of the rest of the laponite batches tested in this study. These are not shown on the same graph for clarity and conciseness.

The results shown in figure 13 indicate that S_u shows a clearly increasing trend with increasing aging time. Such trend is consistent with the rheology test results presented earlier in this paper (see figs. 2 and 3). Also, the

FIG. 13 Variation of undrained shear strength with aging time for 10 different mixtures with varying MLPS content and SPP dosages.



results in **figure 13** show a decreasing rate in the time-dependent S_u gain, reaching an S_u value that could be considered as the ultimate value after 28 days of aging for all mixtures evaluated in this study.

The results show that the S_u at Day 7 exceeded 70 % of the ultimate shear strength for most mixtures. Accordingly, the trends in the S_u obtained after testing samples aged over a 7-day period may be considered a good indicator of the trends expected for the ultimate strength of various laponite mixtures.

EFFECT OF TEMPERATURE

An increase in temperature is anticipated to result in a decrease in the viscosity of materials and, accordingly, would also be expected to lead to a decrease in the S_u. However, Díaz-Rodríguez and Santamarina (1999) reported that the rate of thixotropic strength gain could increase with increasing temperature for clays that show significant thixotropic behavior, a trend that would lead to an increased rate of aging with increasing temperature. The impact of temperature on viscosity as well as on the thixotropic behavior of laponite is expected to be consistent with that of highly sensitive clays. Consequently, an investigation was undertaken in this study to evaluate the effect of temperature on the shear strength of laponite mixes and establish whether the trends on viscosity or thixotropy dominate the observed trends in S_u. The evaluation involved aging selected mixtures (L5-S0.00, L5-S0.06, L5-S1.71, and L8-S0.10) at temperatures of 5°C and 40°C to assess the effect of temperature after aging to 7 and 28 days.

Table 7 shows a summary of the test results, which quantify the S_u of mixtures tested for the following conditions: (1) aging periods of 1, 7, 14, and 28 days at 25°C; (2) aging period of 7 days after initial preparation and subsequent remixing at 25°C; and (3) aging periods of 7 and 28 days at both 5°C and 40°C.

The results presented in **Table 7** indicate that a temperature decrease leads to decreased rates of aging that resulted in decreased S_u values. This is despite the potential increase in viscosity that may have resulted from the decreased temperature. Specifically, the S_u values for the selected mixtures evaluated after aging periods of 7 and 28 days at 5°C were consistently lower than the S_u for the control mixtures at 25°C after the same aging periods.

Also, an increase in S_u was observed in samples tested at the comparatively higher temperature of 40°C (in relation to strength values at a temperature of 25°C), as particularly shown for mixtures L5-S0.00, L5-S0.06 and L5-S1.71. The $S_{u,T=40°C}$ values after an aging period of 7 days essentially matched the $S_{u,T=25°C}$ values after an aging of 28 days, whereas the $S_{u,T=40°C}$ values after 28 days exceeded the $S_{u,T=25°C}$ values after 28 days by a factor of 1.5 to 2.

TABLE 7
Effect of temperature on the undrained shear strength

	S_u, kPa					
	25°C		5°C		40°C	
Mix	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
L5-S0.00	0.313	0.405	0.288	0.34	0.51	0.92
L5-S0.06	0.2	0.295	0.15	0.205	0.28	0.501
L5-S1.71	0.047	0.147	0.02	0.03	0.14	0.213
L8-S0.10	0.666	1.026	0.42	0.65	0.82	1.03

An increase in temperature appears to have increased the thixotropic strength gain, although shear strength results conducted at a temperature of 25°C (fig. 13) show that most mixtures have reached an ultimate strength value after an aging period of 28 days. It should be noted that no volumetric changes were observed during the aging process of the laponite samples. Based on the trend of shear strength results, it is conceivable that $S_{u,T=25°C}$ at Day 28 may continue to increase and reach the ultimate strength value $S_{u,T=40°C}$ after additional aging.

In summary, the results discussed in this section indicate that the S_u increases with increasing laponite content, decreasing SPP dosage, and increasing aging time. Furthermore, an increase in temperature results in an increased thixotropic behavior that leads to comparatively shorter periods to reach the ultimate shear strength of laponite mixtures.

Conclusions

This paper presents a comprehensive evaluation and geotechnical characterization of laponite for use as a transparent clay surrogate. Laponite mixtures were prepared considering a wide range of laponite contents as well as varying SPP additive to understand the parameters of laponite mixtures that govern their behavior. With a plasticity index exceeding 1,000, the execution of geotechnical tests on laponite mixtures was found to be particularly challenging. Yet, a thorough characterization was conducted, which included vane shear tests, rheometer, 1-D consolidation, and Atterberg limits. The results of the experimental program provided significant insight on the geotechnical behavior of laponite, which can be summarized as follows:

- The results from rheology tests revealed two sources of undrained shear strength of laponite after mixing: (1) thixotropic strength gain and (2) particle aggregation strength gain. The apparent viscosity of laponite showed an increasing trend with increased aging time, highlighting the strength gain because of thixotropy.
- The measured liquid limit of laponite mixes was found to be around 1,200 with a plasticity limit of 200. For Casagrande liquid limit test, experiments on varying laponite concentrations and SPP dosages tested under different aging times showed that more energy is needed (higher number of blows) to close the 13-mm groove as aging time increases.
- Results from 1-D consolidation tests indicate that a final level of vertical deformation of around 60–70 % was achieved for different samples at the end of primary consolidation for the highest load stage of 96 kPa. In fact, the consolidation processes were found to lead to laponite contents that are comparatively higher than those achievable through initial mixing. For example, a mixture with an initial laponite content of 11 % reached a final solids content of 21 % at the end of consolidation under a vertical stress of 96 kPa.
- The results of consolidation tests also showed that increasing laponite content led mostly to a decrease in the coefficient of consolidation when the vertical stresses exceed 48 kPa. Compressibility curves for different samples indicated that as the laponite content increases, the compression and swelling indexes decrease. It was also observed that there was loss of transparency in the samples after consolidation ended, and this should be taken into account when researchers later on plan to consolidate laponite samples prior to testing.

- The undrained shear strength of laponite mixes was found to be governed by the laponite content, SPP dosage, and aging time. Specifically, the undrained shear strength was found to increase with increasing laponite content, decreasing SPP dosage, and increasing aging time after initial mixing.
- For the laponite mixtures evaluated in this study, the undrained shear strength was found to approximately double for every 1 % increase in laponite content.
- The relationship between undrained shear strength and SPP dosage revealed that for laponite contents below 8 %, an increase in SPP dosage from 0 to 1.7 % reduced the undrained shear strength by 75 % on average, whereas an increase in SPP dosage from 0 to 3.3 % reduced the undrained shear strength by 85 %. For higher laponite contents, the reductions in undrained shear strengths for an increase in SPP dosage from 0 to 1.7 % and 3.3 % were just 35 % and 40 %, respectively.
- The rate of undrained shear strength increase was particularly high at the initial aging time. For example, an aging time of 7 days was sufficient to reach at least 70 % of the undrained shear strengths achieved at 28 days of aging for most of the mixtures.
- Temperature was found to affect the rate of strength gain of laponite mixtures. For example, an increase in temperature from 25°C to 40°C led to an increase in undrained shear strength after 7 days by factors ranging from 50 to 100 %.

Overall, the use of laponite as a clay surrogate has been deemed to be efficient in mimicking very soft marine clays and could be used in prototype tests as a model material for visualizing internal deformations and failures in the soil matrix. This paper is anticipated to be a great step in moving toward this goal.

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