Study of Undrained Shear Strength of Laponite for Use as Transparent Clay Surrogate

Abdurrahman Almikati, S.M.ASCE[1]; Jorge G. Zornberg, P.E., F.ASCE[2]; and Rodrigo Cesar Pierozan[3]

[1]Postdoctoral Research Fellow, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin. Email: almikati@utexas.edu
[2]Priddy Centennial Professor, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin. Email: zornberg@mail.utexas.edu
[3]Postdoctoral Research Fellow, Dept. of Civil and Environmental Engineering, Pontifical Catholic Univ. of Rio de Janeiro, Rio de Janeiro, Brazil. Email: rodrigopierozan@hotmail.com

ABSTRACT

The use of so-called “transparent soils” as proxy geotechnical materials has allowed for the non-intrusive 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 towards the identification of the undrained shear strengths of laponite mixtures across a wide range of mixes and additive dosages. Results from vane shear tests showed that the undrained shear strength increased with (1) increasing laponite colloid content, (2) decreasing additive dosage, and (3) aging time. 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.

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.

Consistent with the recent advances, transparent soil surrogates can be grouped into four categories: (1) amorphous silica powder that behaves like clays (Iskander et al. 1994); (2) transparent silica gels that behaves like sands (Iskander et al. 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). 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 et al. 2020a).

When mixed with water, MLPS white powder results in a transparent synthetic clay material. This material exhibits very low undrained shear strength values, comparable to those of soft marine clays. A series of published studies have documented efforts to establish geotechnical properties of MLPS 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 tests (Ads et al. 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 practical limitation facing the use of MLPS is the difficulty of preparing mixtures with high solid concentrations, partly because of the comparatively rapid gelation process. In order 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 (Ruzicka and Zaccarelli 2011; Beemer et al. 2016). Specifically, Sodium Pyrophosphate (SPP) has been used in recent studies to facilitate the preparation of MLPS mixtures at relatively high concentrations, producing mixtures of comparatively higher shear strength and stiffness (Ads et al. 2020b). However, only a limited number of mixtures have been evaluated so far, so data is currently not available regarding the strength of mixes prepared for ranges of MLPS 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 MLPS content. In summary, current understanding and control of the impact of increasing SPP dosage on the geotechnical properties of MLPS, while valuable, remains limited.

This paper presents the results of a comprehensive testing program designed and executed to better understand the parameters affecting the undrained shear strength of MLPS mixtures that are relevant for geotechnical modeling using laponite as a clay simulant. The scope of the experimental program includes studying the effects of MLPS content, SPP dosage and aging time of the undrained shear strength of MLPS 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 in the literature as MLPS, produced by BYK Additives and Instruments (2020). MLPS 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).

In order to allow for the preparation of comparatively dense mixes (i.e., to increase the MLPS content of the mixture), Sodium Pyrophosphate (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 entrapped air that allows preparation of comparatively denser MLPS mixtures. The mass percentages of SPP and MLPS used during sample preparation are quantified as follows:

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

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

where C_{SPP} represents the dosage of the rheological additive, C_{lap} represents the MLPS content, m_{SPP} represents the oven-dried mass of SPP, m_{lap} represents the oven-dried mass of MLPS, 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 mas of water m_w, was defined considering the initial moisture content in SPP (68%) and MLPS (8.2%).

The MLPS 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 (2020). Depending on the type of test conducted, mixtures were aged during 0 (i.e., no aging), 1, 7, 14 or 28 days. Note that preparation of mixtures with MLPS 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).

UNDRAINED SHEAR STRENGTH

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

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 MLPS mixtures at a constant speed of 1 rad/min (~60º/min), as recommended by ASTM D4648. 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 blade diameter) below the sample surface, which is consistent with the minimum depth of 1 blade diameter specified in ASTM D4648. A displacement of 1 radian was selected as reference for all tests. Figure 1 depicts the vane shear setup developed in this investigation.

The MLPS content (by dry mass) of the samples tested in this experimental program ranged from 2% to 11%, while the additive dosage ranged from 0.00% to 3.30%. The various mixtures and samples were prepared following the mixing protocols described by Pierozan et al (2021). After mixing, each batch of MLPS slurry was poured into a 600 mL beaker with internal diameter meeting the free border requirements specified in ASTM D4648 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 MLPS Content

A series of laboratory vane shear tests were conducted on 30 transparent clay mixtures involving varying MLPS contents and SPP dosages. The MLPS content ranged from 2 to 11%, which corresponds to MLPS contents that fall in the range of previously reported studies 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 $25°C$.

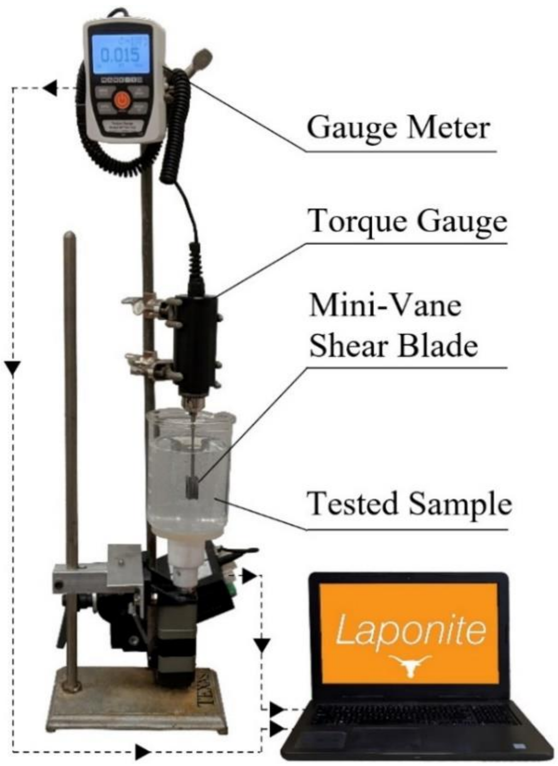

Figure 1. Vane shear setup used for determination of undrained shear strength of different MLPS mixes.

Table 1 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 MLPS 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 1, which indicate peak S_u values often exceeding 1 kPa and reaching up to 2 kPa for mixtures with comparatively high MLPS content achieved by using SPP additive. These comparatively high S_u values were obtained after as early as seven 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, MLPS content, was quantified by comparing the S_u results obtained at a constant temperature (i.e., 25℃), the same aging period, and similar ranges of SPP dosage. The results of such comparison are presented in Figure 2, which indicate that the S_u shows an increasing trend with increasing MLPS content for a given aging period and SPP dosage.

The results in Figure 2(a) correspond to the undrained shear strength S_u of MLPS mixtures prepared without SPP additive (i.e., 0% SPP content). They show a clear increase in S_u with increasing MLPS content. For example, the results for an aging period of one day indicate that the S_u approximately doubles for every 1% increase in MLPS 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 MLPS content for the various ranges of SPP dosage considered in this study, as observed in Figures 2(b), 2(c), 2(d) and 2(e). Also in these cases, S_u approximately doubles for every 1% percent increase in MLPS content.

Table 1: Undrained shear strength for 30 mixtures over time

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

The impact on S_u with increasing MLPS 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 2, the rate of increase of S_u with MLPS content cannot be described by a single variable, as the S_u depends on aspects such as SPP dosage and aging time.

What is also important from these results is that they compare well to previous undrained shear strength studies on MLPS samples with similar concentrations and testing conditions. Ads et al. (2020a) conducted undrained shear strength tests on samples 4.5%, 9% and 13.5 MLPS content, with 0% and 0.405% and 1.992% SPP dosages, respectively. The authors used Miniature Ball Penetrometer (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 to the results in Ads et al. (2020a), where the S_u results for the samples L5-S0.00 and L9-S0.43 in this research compared very well to samples with 4.5% MLPS, 0% SPP and 9% MLPS, 0.405% SPP.

Effect of SPP Dosage

In an attempt to better understand the effect of SPP dosage on the undrained shear strength of MLPS mixtures, an evaluation was conducted by maintaining constant other variables (e.g., MLPS content, aging time, temperature) that also affect the S_u of MLPS. The results presented in Table 1 and Figure 2 indicate that S_u decreases with increasing SPP dosage for a given MLPS content. For example, through referring to the results in bold in Table 1, the S_u reached after 28 days of aging without SPP additive is 1.85 kPa for a MLPS content of 8% [See also Figure 2(a)]; however, for the same aging period and MLPS content, the S_u achieved is only 0.29 kPa when using an SPP dosage of 3.2% [See Figure 2(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 3 shows the effect of SPP dosage on S_u or mixtures prepared using different values of MLPS content and aging periods.

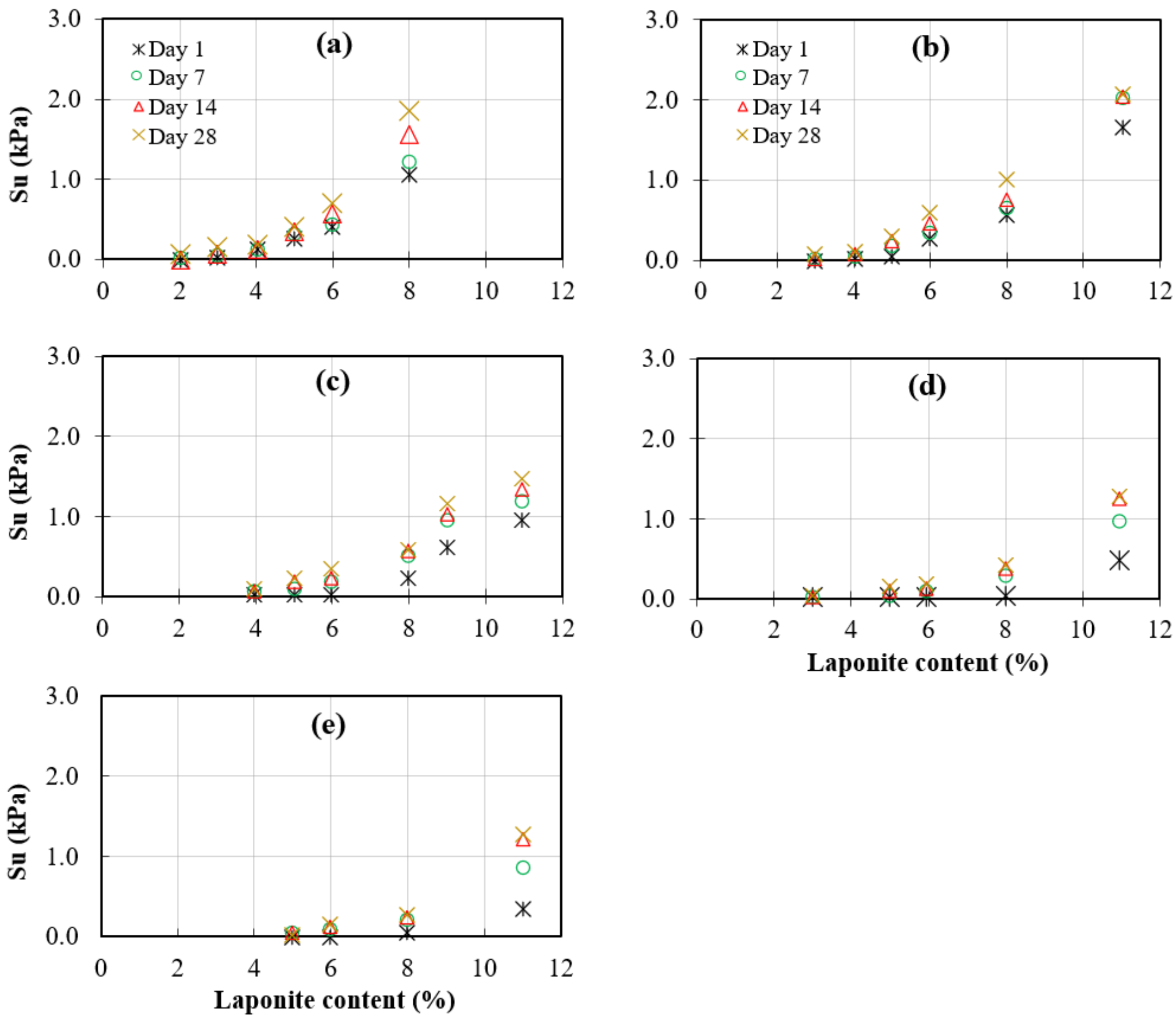

Figure 2. Undrained shear strength for increasing MLPS content after different aging periods for SPP dosages of: (a) 0%; (b) 0.05-0.10%; (c) 0.40-0.50%; (d) 1.6-1.8%.; and (e) 3.0-3.3%.

The results in Figure 3(a) for a MLPS content of 5% and aging period of 1 day show a rapid decrease in S_u with increasing SPP dosage. For this MLPS 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%).

Specifically, as shown in Figure 3(a), S_u for Day 1 dropped about 99% for an increase in SPP dosage from 0% to about 0.5%, with such drop reaching about 100% for an SPP dosage of 1.7%. For aging times of 7, 14 and 28 days, the reduction in strength due to 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 3(b) and 3(c) for MLPS contents of 6 and 8% for the different aging periods is similar to that observed in Figure 3(a) for a MLPS content of 5%.

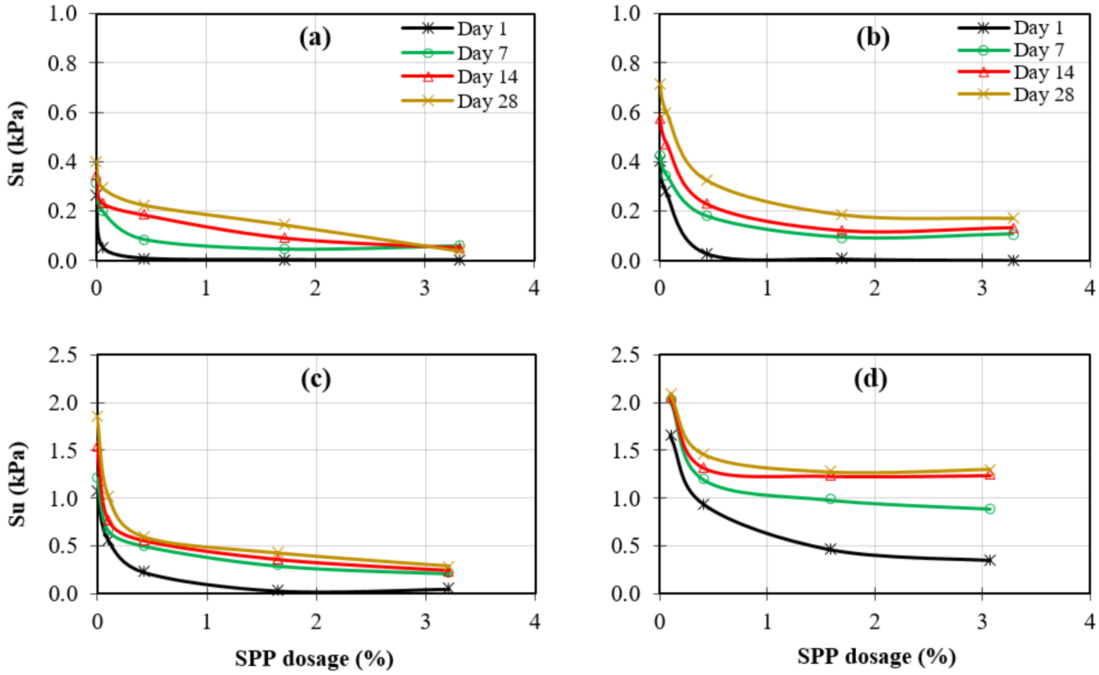

Figure 3. Undrained shear strength variation with SPP dosage at different aging times for MLPS contents of: (a) 5%; (b) 6%; (c) 8%; and (d) 11%.

While the reductions in S_u with increasing SPP dosage showed similar trends for MLPS contents below 8%, the trends were somewhat different for results obtained using a MLPS content of 11%, as shown in Figure 3(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 MLPS concentrations and similar range of SPP dosage [see Figures 3(a), 3(b) and 3(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. Also in this case, the shear strength loss obtained in mixtures with a MLPS content of 11% is also significantly lower than the reductions (ranging from 75% to 85%) obtained when using lower MLPS 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 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 MLPS mixtures can be observed in Figure 4, where the variation of S_u as function of the aging time for 10 MLPS mixtures is presented. The mixtures shown in Figure 4 are representative of the behavior of the rest of the MLPS batches tested in this study. These are not shown on the same graph for clarity and conciseness.

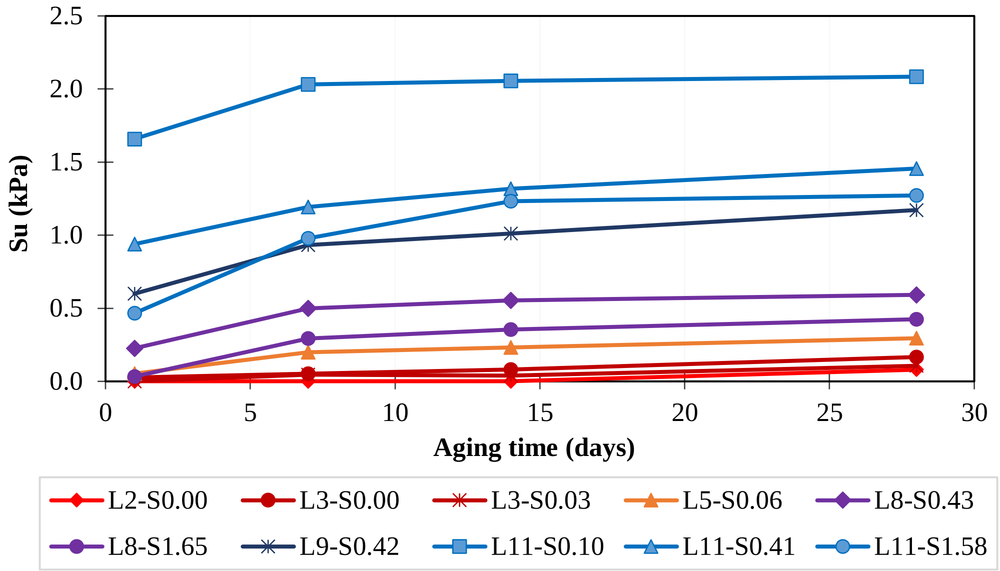

Figure 4. Variation of undrained shear strength with aging time for 10 different mixtures with varying MLPS content and SPP dosages.

The results shown in Figure 4 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 Figures 2 and 3). Also, the results in Figure 4 show a decreasing rate in the time-dependent S_u gain, reaching 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 seven-day period may be considered a good indicator of the trends expected for the ultimate strength of various MLPS mixtures.

CONCLUSIONS

This paper presents a comprehensive evaluation of the three parameters affecting the undrained shear strength of MLPS mixtures: (1) the MLPS content; (2) the SPP dosage; and (3) the aging time. The results of the experimental program provided significant insight on the behavior of MLPS, which can be summarized as follows:

- The undrained shear strength of MLPS mixes was found to be governed by the MLPS content, SPP dosage, and aging time. Specifically, the undrained shear strength was found to increase with increasing MLPS content, decreasing SPP dosage and increasing aging time after initial mixing.
- For the MLPS mixtures evaluated in this study, the undrained shear strength was found to approximately double for every 1% increase in MLPS content.
- The relationship between undrained shear strength and SPP dosage relationship revealed that, for MLPS contents below 8%, an increase in SPP dosage from 0% to 1.7% led to a

reduced, on average, the undrained shear strength by 75%; whereas an increase in SPP dosage from 0% to 3.3% reduced the undrained shear strength by 85%. For higher MLPS 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 initial aging time. For example, an aging time of seven days was sufficient to reach at least 70% of the undrained shear strengths achieved at 28 days aging time for most of the mixtures.

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