Estimating Atterberg Limits of Fine-Grained Soils by Visible–Near-Infrared Spectroscopy

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The Atterberg limits (shrinkage limit [SL], plastic limit [PL], and liquid limit [LL]) describe the physico-mechanical behavior of soils and thus are crucial for civil and agricultural applications. Conventional laboratory methods for measurement of these limits are tedious and costly for a large number of samples. Our objective was to develop visible–near-infrared spectroscopy (Vis-NIRS, from 400–2500 nm) based reliable models to estimate the Atterberg limits. Two conventional methods for each Atterberg limit were used to generate the reference data: paraffin wax and Hg methods for SL; rolling and motorized devices for PL; and Casagrande cup and drop-cone penetrometer methods for LL. Calibration models were built on 80% of the data using partial least squares regression and validated with the remaining 20% of the dataset. The Vis-NIRS independent validation of LL showed very good estimation with standardized RMSE (SRMSE = RMSE/Range) of 0.16 and 0.15, respectively, for LL drop-cone and LL Casagrande methods. Similarly for PL, the Vis-NIRS estimation accuracy was quite good with SRMSE values of 0.18 and 0.22, respectively, for PL motorized and PL rolling. Reasonably good estimation was obtained for the SL paraffin and SL Hg with SRMSE of 0.25 for both methods. The results suggest that the Vis-NIRS calibration models and the accuracy following validation were similar for the pair of methods used for the SL, PL, and LL. Finally, analyses of the model regression coefficients revealed that the important wavelengths to estimate the SL, PL, and LL in the Vis-NIR regions were present across the entire Vis-NIR spectrum and were strongly related to clay type and content.

Core Ideas

- Two methods each to measure each Atterberg limit (SL, PL, and LL) were evaluated.
- A Vis-NIRS technique successfully estimated Atterberg limits for fine-grained soils.
- The Atterberg limits correlated with typical clay signatures in the Vis-NIR spectrum
- Vis-NIRS model performance was independent of the method used to generate the reference data.
in thread rolling by hand, e.g., the pressure applied by hand and a nonuniform diameter of the soil thread (Bobrowski and Griekspoor, 1992). The Casagrande cup and drop-cone penetrometer are standard methods used to measure the LL (ASTM, 2017; British Standards Institution, 2018). The Casagrande method has limitations such as differences in cup weight, drop weight, cutting of groove, and wear of the grooving tool (Houlsby, 1982). Aside from the specific drawbacks of the conventional methods, there are also collective limitations: they are time consuming and expensive, especially if a large number of samples are to be measured. Pedotransfer functions from readily available soil properties such as particle-size distribution and cation exchange capacity have also been used as an alternative to direct methods to measure Atterberg limits (Keller and Drexler, 2012; Seybold et al., 2008). Pedotransfer functions are often site dependent, and the measurement methods of basic properties required for such pedotransfer functions can also be tedious. Evidently, a simple, precise, and rapid methodology is needed for determining Atterberg limits.

Visible near-infrared spectroscopy (Vis-NIRS) is a well-known technology used in soil analysis for its simplicity and rapidity (Nocita et al., 2015; Viscarra Rossel and McBratney, 1998; Soriano-Disla et al., 2013). The Vis-NIRS technique detects and analyzes soil spectral signatures in the visible (350–700 nm) and near-infrared (700–2500 nm) range that depend on moisture, organic matter, Fe oxides, carbonates, and clay minerals. Therefore, combined with multivariate calibration methods, compositional information of soils can be retrieved from their spectra. Soil properties such as water retention (Babaeian et al., 2015; Prittaki-Chrysodonta et al., 2019) and clay minerals (types and quantity) are reportedly well determined by Vis-NIRS (Fang et al., 2018; Kariuki and van der Meer, 2004; Sridharan, 2014) and are important determinants of the Atterberg limits. Thus, the Vis-NIRS technique provides opportunity to link spectral characterization of fine-grained soils with Atterberg limits. Few studies have been conducted to evaluate the application of spectral information to estimate soil engineering properties. For example, Waruru et al. (2014) used NIRS (800–2500 nm) and presented good estimation performance for the PL (11–39%), with a root mean square error of prediction (RMSEP) of 4.6%, and the LL (22–91%), with a RMSEP of 9.9% for Kenyan surface and subsurface soil samples \((n = 120)\). Good estimation performance was also reported for the PL (RMSEP of 0.57) and LL (RMSEP of 0.54) for Ethiopian samples (number of samples and ranges of the limits were not provided) using Vis-NIRS (Yitagesu et al., 2009). More recently, Gupta et al. (2016) used Vis-NIRS and mid-infrared spectroscopy for Indian samples \((n = 182)\) from different depths and showed good accuracy with Vis-NIRS for the PL (9–27%), with a root mean square error of calibration (RMSEC) of 2.60%, and the LL (12–79%) with RMSEC of 8.20%. The SL is important for assessing settlement and estimating the volume stability of engineering soils, yet to the best of our knowledge, there are almost no studies that have estimated the SL with Vis-NIRS.

The tediousness of the measurement methods for the Atterberg limits and the scant knowledge available on the application of Vis-NIRS to estimate the Atterberg limits motivated this study. Therefore, the aim of the study was to develop Vis-NIRS calibration models for estimating the Atterberg limits (SL, PL and LL) of fine-grained soils based on two conventional methods for each limit.

**Materials and Methods**

**Soil Sampling and Reference Measurements**

Eighty-three soil samples were collected from outcrops, foundation excavations, and road cuts at different sites in Ankara, Turkey. The sampling locations ranged from lacustrine deposits to the weathering zones of volcanic rocks. Further details on the samples were provided by Kayabali (2012). The soil samples were air dried, crushed, and passed through a 425-μm sieve.

For this study, the Atterberg limits (SL, PL, and LL) were measured with two conventional methods each (SL, paraffin and Hg method; PL, rolling device and motorized PL test device; and LL, Casagrande and drop-cone methods) to generate reference datasets.

**Shrinkage Limit**

The Hg \(\text{(SL}_{\text{Hg}}\)) and paraffin wax \(\text{(SL}_{\text{paraffin}}\)) methods were used to measure the SL. For the Hg method, the weight of soil paste with shrinkage dish and gravimetric water content was measured. The volume of dry soil past \(V_{\text{d}}\) was measured after placing it in a Hg-filled cup (ASTM, 1998). The shrinkage limit (SL, %) was calculated as

\[
\text{SL} = w \times \left(1 - \frac{V_{\text{d}}}{V_{\text{w}}}ight) \times 100(\%)
\]

where \(\rho_{\text{w}}\) is the density of water \((1.0 \text{g/cm}^3)\), \(w\) is the initial water content of the soil paste (%), \(M_{\text{o}}\) is the weight of the oven-dried sample (g), and \(V\) is the volume of the shrinkage dish \((\text{cm}^3)\).

The paraffin wax method included the same steps as the Hg method until the step for obtaining the gravimetric water content and volume of shrinkage dish. In the paraffin wax method, the dry soil pat was securely tied by a sewing thread and immersed in molten wax, completely coating the pat, which was then left to cool. The mass of the wax-coated pat of soil in the air was afterward recorded. Next, the submerged mass of the wax-coated soil pat was determined (ASTM, 2002). Calculations were done to determine a series of parameters to finally determine the SL in the following manner:

\[
\text{SL} = w \times \left(1 - \frac{V_{\text{d}}}{m_{\text{s}}}ight) \times 100(\%)
\]
where \( w \) is the initial water content of the mixture (%), \( V \) is the volume of the wet soil pat (=volume of the shrinkage dish; cm\(^3\)), \( V_d \) is the volume of the dry soil pat (cm\(^3\)), \( \rho_w \) is the density of water (1.0 g/cm\(^3\)), and \( m_s \) is mass of the dry soil pat (g).

**Plastic Limit**

The PL was determined by the rolling (PL\(_{rolling}\)) and motorized (PL\(_{motorized}\)) PL test devices. The rolling device was used to roll the paste into a thread of 3-mm diameter without breaking. The gravimetric water content at the breaking point of the thread was considered the PL (ASTM, 2001). The basic principle of the motorized PL test device is to roll the paste into threads. The PL is the water content at the moment when the length of threads dropping from the bottom release of the device is between 1 and 2 cm. Further details on the motorized device and methodology were reported by Kayabali (2012).

**Liquid Limit**

The Casagrande cup (LL\(_{Casagrande}\)) and drop-cone penetrometer (LL\(_{drop-cone}\)) methods were used to measure the LL. In the Casagrande cup method, the number of blows required to close a 13-mm-wide groove was counted across a range of water contents. The LL was determined as the gravimetric water content at 25 blows (Casagrande, 1958). The LL from the drop-cone penetrometer method was determined as the water content at which a standard cone penetrated the soil paste to a depth of 20 mm in 5 s (British Standards Institution, 1990).

**Comparison of Conventional Methods**

Scatterplots and the nonparametric Mann–Whitney rank sum test (Mann and Whitney, 1947) were used for method comparison for the SL, PL, and LL due to the non-normal distribution of the data. The scatterplots provide a visual overview of the agreement of data with a regression line, and the Mann–Whitney rank sum test was used to assess the difference between the measurement methods.

**Spectroscopy Measurements**

A commercially available Vis-NIR spectrometer (NIRSTM DS2500, FOSS) was used to measure spectral reflectance of the soil samples. The average temperature and relative humidity in the laboratory during scanning were 21°C and 59%, respectively. The spectrometer was equipped with silicon (400–1100 nm) and lead sulfide (1100–2500 nm) detectors. A white reference (Spectralon) was used to calibrate the instrument prior to the measurements. The digital number of the sample was ratioed against the digital number of the white reference to calculate relative reflectance. The soil spectral reflectance was measured on 50-g soil samples across the visible–near-infrared range (400–2500 nm) with a spectral resolution of 8.75-nm full width at half height and a sampling interval of 0.5 nm. The soil sample was placed in a 7-cm sample cup equipped with a 6-cm quartz window at the bottom. Collected reflectance was converted to absorbance by \( A = \log (R^{-1}) \), where \( R \) is the reflectance. The average spectrum extracted from the collected reflectance from seven locations of the sample cup was used for further analysis.

**Multivariate Data Analysis**

The dataset of 83 samples was divided into two subsets: 80% (\( n = 62 \)) for calibration and 20% (\( n = 21 \)) assigned to a validation dataset to evaluate the model’s performance. The division was done by sorting the dataset according to LL values (from low to high values) due to its wide range compared with the other properties. After sorting, every fourth consecutive sample was taken out for the validation dataset, and the remaining samples were used for the calibration dataset (Esbensen, 2010). We applied partial least square regression in Unscrambler X 10.5.1 software (Camo ASA) to model the relationship between the measured SL, PL, and LL data and the Vis-NIR spectral absorbance values. Prior to calibration (leave-one-out full cross-validation) development, the spectra were transformed by a Savitzky–Golay derivative (Savitzky and Golay, 1964). A second-order derivative, second-order polynomial, and 31 smoothing points—15 left points and 15 right points—were applied.

**Evaluation of Model Performance**

The estimation ability of the models was evaluated by the square of the Pearson correlation coefficient (\( R^2 \)) and the root mean square error of cross-validation (RMSECV). The RMSEP was additionally used to evaluate the independent validation accuracy. The RMSE and standardized RMSE (SRMSE) were calculated as:

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum (\text{Atterberg limit}_p - \text{Atterberg limit}_r)^2},
\]

where Atterberg limit\(_p\) and Atterberg limit\(_r\) are the estimated and reference values of SL, PL, or LL, and \( N \) is the number of samples.

The RMSE value is strongly influenced by the range of measured values of the considered soil property. Thus, to compare the cross-validation model and performance of the model with other studies, the SRMSE (Arthur, 2017; Rehman et al., 2019) was used:

\[
\text{SRMSE} = \frac{\text{RMSE}}{\text{Range}}
\]

where Range represents the largest minus the smallest SL, PL, or LL for the respective dataset or published study. Smaller SRMSE values denote better estimations and vice versa.

**Results and Discussion**

**Descriptive Statistics of Soil Attributes**

A summary of descriptive statistics of the Atterberg limits and basic soil properties are given in Table 1. The range for the three limits for the two respective conventional methods were similar; however, the most variable limit was the LL with the Casagrande method, with a range of 47%. Soil samples were fine
grained with an average clay content of 36% and silt content of 54%. The organic matter content in the collected samples was generally low (data not available). Supplementary information on the soil properties for each individual sample is provided in Supplemental Table S1.

**Comparison of Methods**

The aim behind the method comparison was to assess the possible difference between the paraffin and Hg methods for SL, the rolling device and motorized device methods for PL, and the Casagrande and drop-cone methods for LL. A significant scatter of the data points around the regression line can be observed in Fig. 1a and 1b for the paraffin and Hg methods ($R^2 = 0.77$) and the rolling device and motorized device methods ($R^2 = 0.72$), whereas there was a significant linear relationship between the Casagrande and drop-cone methods ($R^2 = 0.99$) (Fig. 1c). The values obtained by the drop-cone method were marginally larger than the Casagrande method, and our results agree with those available in the literature (Spagnoli, 2012; Sridharan and Prakash, 2000). There were some discrepancies between the methods for the SL and PL, as can be seen in Fig. 1a and 1b. The SL obtained by paraffin showed smaller values than the Hg method, whereas the rolling device gave larger values than the motorized device for the PL. To the best of our knowledge, no other studies are available in the literature to compare the measurement method (paraffin and Hg) results for the SL. Additionally, the rank sum test showed a smaller median difference (2.6%) between the Casagrande and drop-cone methods for the LL. For the SL, the median difference between the paraffin and Hg methods was 3.2%. A much larger median difference of 7.0% was observed for the PL for the rolling device and motorized device methods. Based on the median values, there was no statistically significant difference between the Casagrande and drop-cone methods ($p$ value = 0.090); however, there was a statistically significant difference ($p$ value < 0.001) between the methodologies for the SL and PL.

**Calibration of Atterberg Limits**

The strength of correlation of soil spectra and Atterberg limits was independent of the conventional methods used for measuring the limits (Fig. 2). It can be seen in Fig. 2 that there was no significant difference between the results obtained based on the different conventional methods for the SL, PL, and LL. For each limit, the method with the highest $R^2$ and lowest RMSECV was selected for the discussion of the agreement between the spectra and measured data and also to make a comparison with the results available in the literature. Good calibrations of the SL, PL, and LL to Vis-NIR

### Table 1. General statistics for entire ($n = 83$), calibration ($n = 62$), and independent validation ($n = 21$) datasets.

<table>
<thead>
<tr>
<th>Property</th>
<th>Method</th>
<th>Mean</th>
<th>Max.</th>
<th>Min.</th>
<th>Range</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage limit</td>
<td>paraffin</td>
<td>16 (16, 15)</td>
<td>27 (27, 25)</td>
<td>10 (10, 10)</td>
<td>17 (17, 14)</td>
<td>4 (4, 4)</td>
</tr>
<tr>
<td></td>
<td>Hg</td>
<td>18 (18, 18)</td>
<td>30 (30, 27)</td>
<td>10 (10, 10)</td>
<td>21 (21, 15)</td>
<td>5 (5, 5)</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>motorized</td>
<td>24 (25, 23)</td>
<td>35 (35, 33)</td>
<td>18 (19, 18)</td>
<td>18 (17, 15)</td>
<td>4 (4, 4)</td>
</tr>
<tr>
<td></td>
<td>rolling device</td>
<td>31 (31, 30)</td>
<td>41 (41, 37)</td>
<td>24 (24, 24)</td>
<td>17 (17, 13)</td>
<td>4 (4, 4)</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>Casagrande</td>
<td>62 (63, 62)</td>
<td>90 (90, 78)</td>
<td>43 (46, 43)</td>
<td>47 (44, 36)</td>
<td>9 (9, 9)</td>
</tr>
<tr>
<td></td>
<td>drop cone</td>
<td>65 (65, 64)</td>
<td>91 (91, 81)</td>
<td>46 (50, 46)</td>
<td>45 (41, 35)</td>
<td>9 (9, 10)</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td>36 (35, 40)</td>
<td>68 (62, 68)</td>
<td>11 (11, 16)</td>
<td>57 (51, 52)</td>
<td>14 (14, 17)</td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td>54 (55, 51)</td>
<td>85 (85, 80)</td>
<td>28 (28, 30)</td>
<td>57 (57, 51)</td>
<td>15 (15, 14)</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td>10 (10, 9)</td>
<td>32 (32, 32)</td>
<td>0 (0, 0)</td>
<td>32 (32, 32)</td>
<td>11 (10, 12)</td>
</tr>
</tbody>
</table>

† The first value is for the entire dataset; values for the calibration dataset followed by the validation dataset are given in parentheses.

![Fig. 1. Scatterplot comparison of (a) the shrinkage limit (SL) by the paraffin wax and Hg methods, (b) the plastic limit (PL) by the motorized and rolling device methods, and (c) the liquid limit (LL) by the Casagrande and drop-cone methods.](image-url)
spectral reflectance data were obtained, with RMSECV values of 2.89, 2.43, and 6.94% and SRMSE values of 0.17, 0.15, and 0.16, respectively. The Vis-NIRS partial least square regression provided a better correlation between the soil spectral data and measured data for the PL compared with the SL and LL (Fig. 2). The Vis-NIRS cross-validation of the PL showed similar estimation accuracy as the results reported by Waruru et al. (2014) for 136 Kenyan soils with an $R^2$ value of 0.5, SRMSE of 0.14, and RMSECV of 4.1%. Gupta et al. (2016) presented similar accuracy for the PL for 182 Indian soils, with $R^2$ of 0.62 and SRMSE of 0.14. The observed ability of Vis-NIRS to estimate the PL is due to the fact that the PL is strongly related to soil water content, and water content is strongly negatively correlated with reflectance in the NIR region (Marakkala Manage et al., 2018; Mouazen et al., 2006). The accuracy of the estimated LL, with SRMSE of 0.16, is slightly lower than that reported by Gupta et al. (2016), with a SRMSE of 0.12, and by Waruru et al. (2014) in the NIR region, with a SRMSE of 0.10.

Regression Coefficients and Important Wavelengths

The regression coefficients obtained at each spectral wavelength for SL$_{paraffin}$ and SL$_{Hg}$, PL$_{motorized}$ and PL$_{rolling}$, and LL$_{Casagrande}$ and LL$_{drop-cone}$ methods are presented in Fig. 3. In Table 2, a comparison with the literature of the important wavelengths obtained in this study for each Atterberg limit is provided.

Shrinkage Limit

In the visible range, pronounced peaks (at 420 and 451 nm) for the SL and the two conventional methods can be observed. Important but less pronounced regression coefficients were also observed around 720 nm. In the NIR region, based on both conventional methods, the highest regression coefficients for the SL occurred around 2300 and 2320 nm. Multiple important peaks were observed around 1410 and 1914 nm. Additionally, a high regression coefficient was observed around 1140 nm with the Hg method (Fig. 3a).
Plastic Limit

The important wavelengths in the visible range for the PL were observed around 500 and 600 nm and were also reported in the literature (Table 2). Similar to the SL, an important noticeable peak for the PL with the rolling device method was observed at wavelength 1140 nm; there is currently no study reporting regression coefficients for the Vis-NIRS estimation of PL. Other significant peaks at 1410, 1914, 2320, and 2350 nm with both conventional methods were observed in this study (Fig. 3b).

Liquid Limit

Multiple peaks at 451, 500, 520, and 620 nm were observed for the LL in the visible region, similar to the wavelengths reported in the literature (Table 2). Based on both conventional methods, a high peak at 1130 nm can be identified. There is no evidence in previous research regarding 1130 nm for the LL. The NIR region also showed significant peaks at 1410, 1914, 2320, and 2350 nm with both conventional methods were observed in this study (Fig. 3c).

Discussion of Regression Coefficients

The observed peaks for the SL, PL, and LL in the visible region (400–700 nm) can be assigned to Fe oxide minerals (goethite and hematite) (Viscarra Rossel and Behrens, 2010; Sherman and Waite, 1985) and organic matter (Ben-Dor et al., 1997). Iron oxide minerals present in amorphous clay-size particles have a strong effect on soil expansiveness (Wan et al., 2002). Furthermore, studies have consistently shown a positive relationship between organic matter content and the PL and LL (Keller and Dexter, 2012; Stanchi et al., 2009).

In this study, the wavelengths for the SL, PL, and LL observed in the NIR range around 2300, 2320, 2350, 2355, and 2425 nm can be attributed to a combination of Al–OH bending and O–H stretching vibrations, Fe–OH bending, and C–H bonds (Ben-Dor et al., 1997; Goetz et al., 2001; Madejová et al., 2009; Stenberg et al., 2010), all being typical for clay minerals. The peaks for the SL, PL, and LL around 1410, 1914, and 1910 nm are related to the combination of H–O–H bending vibrations and asymmetric O–H stretching vibrations (Hunt, 1977). The observed peaks are linked to the combination of symmetric and asymmetric O–H stretching vibrations and the first overtone of O–H stretch in the octahedral layer of clay minerals (Clark et al., 1990; Hunt, 1977; Madejová et al., 2009). Additionally, in this study a high regression coefficient for the SL, PL, and LL was observed around 1140 nm; however, no component was found in the literature that linked to observed regression coefficient, although wavelengths at 1135 nm are linked to free water, 1160 nm is linked to organic matter, and C=O bonds were found in the literature (Hunt, 1977; Shonk et al., 1991). Collectively important absorption bands in the NIR region explained the fact that Atterberg limits are directly associated with clay (type and content). These absorption bands explain the link with different types of O–H bonds in the NIR region, consequently contributing to estimating the Atterberg limits.

Independent Validation of Atterberg Limits

The Vis-NIRS validation results for the SL, PL, and LL are presented in Fig. 4. It can be observed that the estimation of the limits from spectral data was independent of the conventional methods used for measuring the reference data. For instance, the developed calibration models estimated the LL (RMSEP = 5.23% and SRMSE = 0.15) and PL (RMSEP = 2.80% and SRMSE = 0.18) to a reasonable degree of accuracy but was a bit less accurate for SL estimation (RMSEP = 3.61% and SRMSE = 0.25) (Fig. 4). The observed performance of the models reflects the stable relationship between Atterberg limits and spectrally active soil components such as clay mineralogy, clay content, and moisture content. Few studies have reported independent validation of Vis-NIRS determination of the PL and LL (Yitagesu et al., 2009) and of NIRS
determination of the PL and LL (Waruru et al., 2014). Yitagesu et al. (2009) reported good accuracy for the PL ($R^2 = 0.71$ and RMSEP = 0.57) and LL ($R^2 = 0.87$ and RMSEP = 0.54); however, neither the number of samples nor the limits’ ranges were reported. The estimation accuracy for the LL ($R^2 = 0.71$, RMSEP = 5.23%, and SRMSE = 0.15) is comparable to results by Waruru et al. (2014), who reported $R^2$ of 0.74, RMSEP of 9.9%, and SRMSE = 0.13. The visible and NIR region from the current study and the NIR region from the Waruru et al. (2014) study used to estimate the PL showed lower accuracy. The lower accuracy could be due to the smaller range and variation of limits used for the development of the Vis-NIRS cross-validation model and independent validation.

**Conclusions**

The Atterberg limits (SL, PL, and LL) estimated by Vis-NIRS were in good agreement with the conventional methods. The Vis-NIRS technique demonstrated high accuracy for the LL and PL and acceptable accuracy for SL estimations. Successful application of Vis-NIRS to Atterberg limits determination was attributed to a strong correlation of the Atterberg limits with spectrally active components related to soil clay mineralogy (mainly O–H bonds and Fe oxides).

Conventional methods comparison revealed a good correlation between paraffin wax and Hg methods for the SL, the rolling device and motorized methods for the PL, and the Casagrande cup and drop-cone penetrometer methods for the LL. The Vis-NIRS approach showed similar prediction accuracy for the SL, PL, and LL regardless of the conventional method used to generate the reference dataset. Hence, it can be concluded that Vis-NIRS can be used as an alternative to conventional methods for fast estimation of the Atterberg limits for Turkish soils.

**Supplemental Material**

The supplemental material includes information regarding soil texture and Atterberg limits of the investigated soil samples (Table S1). Additionally, it contains the Atterberg limits (shrinkage limit, plastic limit, and liquid limit) calibration models for use and validation by other researchers (Table S2).

**Acknowledgments**

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**References**


**Fig. 4.** Scatterplots of independent validation of measured and visible–near-infrared spectroscopy (Vis-NIRS) estimated values of the (a) shrinkage limit (SL) by paraffin and Hg, (b) PL plastic limit by the motorized and rolling devices, and (c) liquid limit (LL) by Casagrande and drop-cone methods. Also shown are Pearson’s correlation coefficient ($R^2$), the root mean square error of prediction (RMSP), and the standardized RMSE (SRMSE) for each method.