



Statistical Reappraisal of the Wax and Mercury Methods for Shrinkage Limit Determinations of Fine-Grained Soils

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Abstract Because of the hazards associated with handling mercury, most standards organizations have withdrawn the conventional mercury (displacement) method (MM) for shrinkage limit (SL) determination of fine-grained soils. Despite attempts to substantiate the wax (coating) method (WM), which is presently the only standardized MM-testing alternative, the geotechnical community remains somewhat hesitant of its adoption in routine practice. To encourage more widespread use of WM-testing, this study re-examines the level of agreement between the MM- and WM-deduced SL parameters (i.e., SL_{MM} and SL_{WM} , respectively). This was achieved by performing comprehensive statistical analyses on the largest and most diverse database of its kind, to date, entailing $SL_{MM}:SL_{WM}$ measurements for 168 different fine-grained soils having wide ranges of plasticity

characteristics (i.e., liquid limit = 31.6–362.0%, plasticity index = 8.2–318.0% and $SL_{MM} = 7.1–42.0\%$). Furthermore, an attempt was made to evaluate the SL_{WM} (in lieu of the SL_{MM}) parameter for performing preliminary soil expansivity assessments using existing SL_{MM} -based classification approaches. It was demonstrated that the MM and WM methods do not produce identical SL values for a given fine-grained soil under similar testing conditions, with their discrepancy being systematic and hence likely arising from the differences between the materials (mercury versus wax) and methodologies involved in performing these tests. New $SL_{WM} \rightarrow SL_{MM}$ conversion relationships were established, allowing SL_{MM} to be deduced as a function of SL_{WM} with high accuracy. Hence, when inputting SL_{WM} in SL_{MM} -based

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empirical correlations to predict other geoengineering design parameters, the newly proposed conversion relationships can be employed to minimize systematic prediction errors. It was also demonstrated that plasticity-based correlations, at best, can only provide a rough approximation of SL_{MM} . Hence, when the SL is desired, WM-testing or any other alternative method that directly and reliably measures the soil shrinkage factors should be retained. Finally, the same soil-expansivity rankings, as obtained for existing classification systems employing SL_{MM} results, are achieved using SL_{WM} measurements (i.e., without the need of applying $SL_{WM} \rightarrow SL_{MM}$ conversion equations).

Keywords Fine-grained soil · Shrinkage limit · Mercury displacement · Wax coating · Soil plasticity · Soil expansivity

Abbreviations

%WC	Percent gravimetric water content
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BS	British Standard
CE	Clay (C) with extremely high (E) plasticity
CH	Clay (C) with high (H) plasticity
CI	Clay (C) with intermediate (I) plasticity
CL	Clay (C) with low (L) plasticity
CV	Clay (C) with very high (V) plasticity
IS	Indian Standard
ME	Silt (M) with extremely high (E) plasticity
MH	Silt (M) with high (H) plasticity
MI	Silt (M) with intermediate (I) plasticity
ML	Silt (M) with low (L) plasticity
MM	Mercury (displacement) method

MV	Silt (M) with very high (V) plasticity
N TL	Normal-shrinkage tangent line
TMD	Tukey Mean–Difference (plot/method)
WM	Wax (coating) method
ZTL	Zero-shrinkage tangent line

List of Symbols

A_c	Soil activity ($= PI/f_{clay}$) (–)
CAL	Soil-expansivity classification agreement level (%)
e	Void ratio (–)
f_{clay}	Clay ($< 2 \mu m$) content (%)
f_{fines}	Fines ($< 75 \mu m$) content (%)
f_{sand}	Sand ($> 75 \mu m$) content (%)
f_{silt}	Silt ($2–75 \mu m$) content (%)
G_s	Specific gravity of soil solids (–)
$LAL_{95\%}$	95% lower statistical agreement limit (%WC)
LL	Liquid limit (%WC)
LL_{UA}	LL at the intersection of the U and A lines of the soil plasticity chart ($LL_{UA} = -43.53\%$)
m	Summation index (–)
M_D	Mass of oven-dried soil test specimen (SL test) (g)
M_{dm}	Mass of mercury displaced by oven-dried soil test specimen (SL_{MM} test) (g)
M_{sxa}	Mass of wax-coated oven-dried soil test specimen in air (SL_{WM} test) (g)
M_{sxw}	Mass of wax-coated oven-dried soil test specimen in water (SL_{WM} test) (g)
N_C	Number of clay soils (–)
N_D	Number of soil-expansivity classification discrepancies (–)
N_M	Number of silt soils (–)
NRMSE	Normalized root-mean-squared error (%)

N_S	Number of soil materials (or SL_{MM} : SL_{WM} data pairs) investigated (–)	$\mu[\delta_M]$	Arithmetic mean of δ_M data (%WC)
PI	Plasticity index (= $LL - PL$) (%WC)	ρ_m	Density of mercury (g/cm^3)
PI_{UA}	PI at the intersection of the U and A lines of the soil plasticity chart ($PI_{UA} = -46.38\%$)	ρ_w	Density of water (g/cm^3)
PL	Plastic limit (%WC)	ρ_x	Density of paraffin wax (g/cm^3)
R^2	Coefficient of determination (–)	$\sigma[\delta_M]$	Standard deviation of δ_M data (%WC)
RMSE	Root-mean-squared error (%WC)		
SI	Shrinkage index (= $LL - SL$) (%WC)		
SI_{MM}	MM-based shrinkage index (= $LL - SL_{MM}$) (%WC)		
SI_{WM}	WM-based shrinkage index (= $LL - SL_{WM}$) (%WC)		
SL	Shrinkage limit (%WC)		
SL_{MM}	MM shrinkage limit (%WC)		
$SL_{MM(max)}$	Maximum of SL_{MM} data (%WC)		
$SL_{MM(min)}$	Minimum of SL_{MM} data (%WC)		
SL_P	Predicted shrinkage limit (as a function of LL and PI) (%WC)		
SL_{WM}	WM shrinkage limit (%WC)		
$UAL_{95\%}$	95% upper statistical agreement limit (%WC)		
V_A	Initial volume of remolded soil paste specimen (SL test) (cm^3)		
V_D	Volume of oven-dried soil test specimen (SL test) (cm^3)		
w	Gravimetric water content (%WC)		
w_A	Initial gravimetric water content of remolded soil paste specimen (SL test) (%WC)		
δ_M	Shrinkage limit prediction residual (= $SL_{WM} - SL_{MM}$ or $SL_P - SL_{MM}$) (%WC)		

1 Introduction

Since their introduction by Albert Atterberg in the early 1910s (Atterberg 1911a, b), the liquid, plastic and shrinkage limits (i.e., LL, PL and SL, respectively), collectively termed as the ‘Atterberg limits’, remain among the most commonly specified soil parameters in geoenvironmental practice. The Atterberg limits—together with the shrinkage and plasticity indices, numerically defined as $SI = LL - SL$ (IS 1498 1970; Sridharan and Nagaraj 2000) and $PI = LL - PL$, respectively—describe changes in the consistency states (and hence mechanical behavior) of fine-grained soils with varying water content. Conceptually, the LL, PL and SL represent limiting water contents at which fine-grained soil undergoes $liquid \xrightarrow{LL} plastic \xrightarrow{PL} semi-solid \xrightarrow{SL} solid$ transitions in consistency (see Fig. 1). The SL-state water content (the least commonly specified/employed of the Atterberg limits in practice) is defined as the water content below which no further reduction

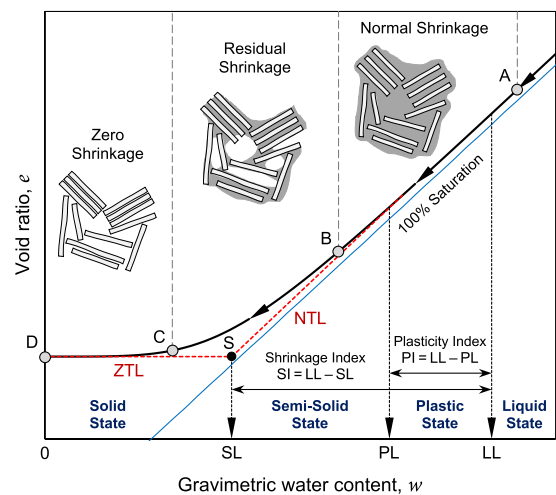


Fig. 1 Conceptual illustration of the shrinkage behavior of remolded (non-structured) fine-grained soils

in bulk soil volume takes place during (uniform) drying. As such, the SL parameter can be viewed as a proxy to “*evaluate the shrinkage potential or possibility of development, or both, of cracks in earthworks involving cohesive soils*” (ASTM D427 2004). Other useful applications for the SL, mainly when employed in conjunction with the LL and/or PI parameters, include performing preliminary soil expansivity (volume change) assessments (e.g., Altmeyer 1955; Holtz 1959; Ranganatham and Satyanarayan 1965; Raman 1967; IS 1498 1970; Sowers and Sowers 1970; Dakshanamurthy and Raman 1973), predicting fabric evolution in stabilized soils (e.g., Sivapullaiah et al. 2000; Sivapullaiah 2015; Soltani et al. 2022), and even estimating important geoenvironmental design parameters, particularly primary consolidation attributes (e.g., Sridharan and Nagaraj 2000, 2004, 2005; Yukselen-Aksoy et al. 2008; Vinod and Bindu 2010; Prakash et al. 2012; Shimobe and Spagnoli 2022).

Referring to Fig. 1; the shrinkage behavior of a remolded (non-structured) saturated fine-grained soil (<425 µm) paste specimen, when dried from a water content initially close to its LL (i.e., Point A), can be conceptualized by three graphically distinguishable stages in the space of void ratio e and gravimetric water content w (Haines 1923; Mitchell 1992; Chertkov 2000; Peng and Horn 2005; Cornelis et al. 2006; Lu and Dong 2017): (i) normal (also known as primary, basic or proportional) shrinkage (i.e., Path $\overline{AB}$); (ii) residual or transitional shrinkage (i.e., Path $\overline{BC}$); and (iii) zero shrinkage (i.e., Path $\overline{CD}$). The normal shrinkage phase evolves linearly along the 100% saturation line (i.e., $e = G_s \times w$, where G_s denotes the specific gravity of soil solids), indicating that any decrease in water volume (during drying) leads to an equal decrease in the bulk soil volume (i.e., $\Delta e / \Delta w \cong G_s$). This relationship is usually expressed in terms of the shrinkage ratio parameter, obtained as the ratio of the specimen volumetric strain (i.e., expressed in percentage terms of the final dry volume) to the corresponding change in water content above the SL. The normal shrinkage stage continues until such time that the soil particles come into close contact with each other, and the moisture present is just sufficient to fully saturate the intra-assemblage pore spaces. Residual shrinkage marks the entrance of air into the intra-assemblage pores, thereby promoting air-filled porosity coupled with a dense particle configuration. During this phase of the shrinkage process, the

volume of lost water exceeds the decrease in bulk soil volume (i.e., $\Delta e / \Delta w < G_s$). Residual shrinkage is followed by the zero-shrinkage phase during which the bulk soil volume remains unaltered as the soil water content further decreases towards the oven-dried state (i.e., $\Delta e / \Delta w \cong 0$). Following the conceptual graphical construction outlined in Fig. 1, the water content at the intersection of the normal- and zero-shrinkage tangent lines (i.e., NTL and ZTL, respectively), shown as Point S in the figure, is defined as the SL parameter (BS 1377–2 1990; Hobbs et al. 2014). In practice, however, the curvilinear shrinkage response is commonly assumed to be bilinear (i.e., Path $\overline{ASD}$), thereby allowing the SL-state water content (in percent water content or %WC) to be deduced as follows (e.g., IS 2720–6 1972; BS 1377–2 1990; ASTM D427 2004; AASHTO T92 2009; ASTM D4943 2018):

$$SL = \left[w_A - \frac{\rho_w (V_A - V_D)}{M_D} \right] \times 100\% \quad (1)$$

where w_A and V_A = initial gravimetric water content (dimensionless) and volume (in cm^3) of the remolded soil paste specimen (i.e., Point A in Fig. 1), respectively; M_D and V_D = oven-dried mass (in g) and volume (in cm^3) of the soil test specimen (i.e., Point D in Fig. 1), respectively; and ρ_w = density of water ($= 1 \text{ g/cm}^3$).

The critical task in deducing the SL-state water content using Eq. (1) is measuring the volume of the oven-dried soil test specimen V_D , with the original approach involving the use of a mercury (because of its very high inter-molecular cohesion) bath, commonly recognized as the mercury (displacement) method (i.e., the SL_{MM} test) (e.g., IS 2720–6 1972; BS 1377–2 1990; ASTM D427 2004; AASHTO T92 2009). Following the mercury method (MM) in accordance with ASTM D427 (2004), a fine-grained soil (<425 µm) paste, prepared at a water content close to its LL (i.e., w_A in Eq. (1)), is remolded into a porcelain dish (with known dimensions) and allowed to air-dry until its color changes slightly, after which oven-drying is performed at $110 \pm 5^\circ \text{C}$ for 24 h. The oven-dried soil test specimen is then immersed in a glass cup full of mercury; the volume of mercury displaced by the specimen is collected and its mass is recorded as M_{dm} . Finally, the volume of the oven-dried soil test specimen is calculated as $V_D = M_{dm} / \rho_m$ (where ρ_m denotes the density of mercury). Note that the conventional MM test can be overly dependent on

operator performance—that is, mercury is a highly dense substance and hence extra (or missing) drops of mercury in the volume displacement evaluations can significantly alter the deduced SL_{MM} value, with this source of error being likely more pronounced when dealing with high plasticity soils that often undergo cracking during drying (Cerato and Lutenege 2006; Estabragh et al. 2013). Furthermore, in response to the occupational health and safety hazards associated with handling mercury, most standards organizations have withdrawn the MM test, including, for instance, ASTM in 2008. The wax (coating) method (i.e., the SL_{WM} test), initially approved by ASTM in 1989, is presently the only standardized alternative to MM-testing. The current edition of the wax method (WM) described in ASTM D4943 (2018) employs the Archimedes' principle to measure V_D (and hence deduce the SL parameter by Eq. (1)) as follows. The oven-dried soil test specimen of mass M_D is provided with a surface coating of wax by its immersion in molten paraffin wax, removal and then allowing the wax-coated specimen to cool to room temperature, after which its mass is recorded as M_{sxa} . The wax-coated specimen is then submerged in water (using a suspension apparatus) and its underwater mass is recorded as M_{sww} . Finally, the volume of the oven-dried soil test specimen is calculated as $V_D = (M_{sxa} - M_{sww})/\rho_w - (M_{sxa} - M_D)/\rho_x$ (where ρ_x denotes the density of the employed paraffin wax).

Despite several attempts to substantiate the WM test (e.g., Prakash et al. 2009; Kayabali 2011, 2013; Rehman et al. 2019; Özer and Yavuz 2021; Pratama et al. 2021), the geotechnical community remains somewhat hesitant of its adoption in routine practice. That is, the withdrawal of MM-testing for SL determination of fine-grained soils has been met by the following undesirable outcomes: (i) removing the SL parameter from routine soil identification tests, reinforced by the notion that this Atterberg limit has relatively limited practical significance compared to the LL and PL parameters; (ii) relying on empirical-type correlations to estimate SL_{MM} as a function of soil plasticity; or (iii) continuing the use of the MM test, with this practice being more prevalent in geotechnical engineering research (e.g., Jha et al. 2020; Sujatha et al. 2021; Süt Ünver et al. 2021; Pradeep and Mayakrishnan 2023; Prakash et al. 2024). Given that the MM (ASTM D427 2004) and WM (ASTM D4943 2018) tests offer similar degrees of repeatability and

Table 1 Summary of the compiled database of $N_S = 168$ SL_{MM} , SL_{WM} test results

Source	N_S	Soil ID	f_{clay} (%)	f_{fines} (%)	LL (%)	LL (%)	PI (%)	$A_c = PI/f_{clay}$	SL_{MM} (%WC)	Standard	SL_{WM} (%WC)	Standard
Prakash et al. (2009)	7	S_1-S_7	–	–	60.0–362.0	–	30.0–318.0	–	13.0–28.0	ASTM D427 (1998)	12.0–31.0	ASTM D4943 (2002)
Kayabali (2011)	46	S_8-S_{53}	–	–	52.6–87.2	ASTM D4318 (2000)	18.7–54.5	–	11.6–31.6	ASTM D427 (1998)	9.8–29.8	ASTM D4943 (2002)
Rehman et al. (2019)	83	$S_{54}-S_{136}$	11–68	67–100	42.9–90.3	ASTM D4318 (2000)	16.7–55.1	0.39–2.23	9.8–30.3	ASTM D427 (1998)	9.9–26.7	ASTM D4943 (2002)
Özer and Yavuz (2021)	22	$S_{137}-S_{158}$	–	30–100	31.6–89.1	ASTM D4318 (2017)	8.2–57.7	–	7.1–18.0	ASTM D427 (2004)	7.5–17.9	ASTM D4943 (2018)
Pratama et al. (2021)	10	$S_{159}-S_{168}$	11–69	52–100	58.0–96.0	–	14.0–52.0	0.52–1.89	17.7–42.0	ASTM D427 (2004)	17.2–39.2	ASTM D4943 (2008)

N_S , number of soil materials (or SL_{MM} , SL_{WM} data pairs) investigated; f_{clay} and f_{fines} = clay (< 2 μ m) and fines (< 75 μ m) fractions, respectively; %WC, percent water content; A_c , soil activity

reproducibility for SL determination of fine-grained soils, it is the authors' viewpoint that greater and more widespread use of the SL_{WM} parameter would be encouraged by statistical demonstration of its agreement with the conventional SL_{MM} parameter through investigating a range of diverse fine-grained soils.

In view of the above, this paper revisits the SL_{MM} : SL_{WM} relationship to better understand the true potentials and/or limitations of WM-testing for SL determination of fine-grained soils. This is achieved by performing a series of critical statistical

analyses using the largest and most diverse database of its kind, to date, consisting of SL_{MM} : SL_{WM} measurements for 168 different fine-grained soil materials (with $LL=31.6\text{--}362.0\%$ WC and $PI=8.2\text{--}318.0\%$ WC). The reliability of empirical-type correlations in estimating SL_{MM} as a function of soil plasticity is also investigated. Finally, an attempt, for the first time, is made to evaluate the SL_{WM} (i.e., in lieu of the SL_{MM}) parameter for soil expansivity assessments using existing SL_{MM} -based classification approaches.

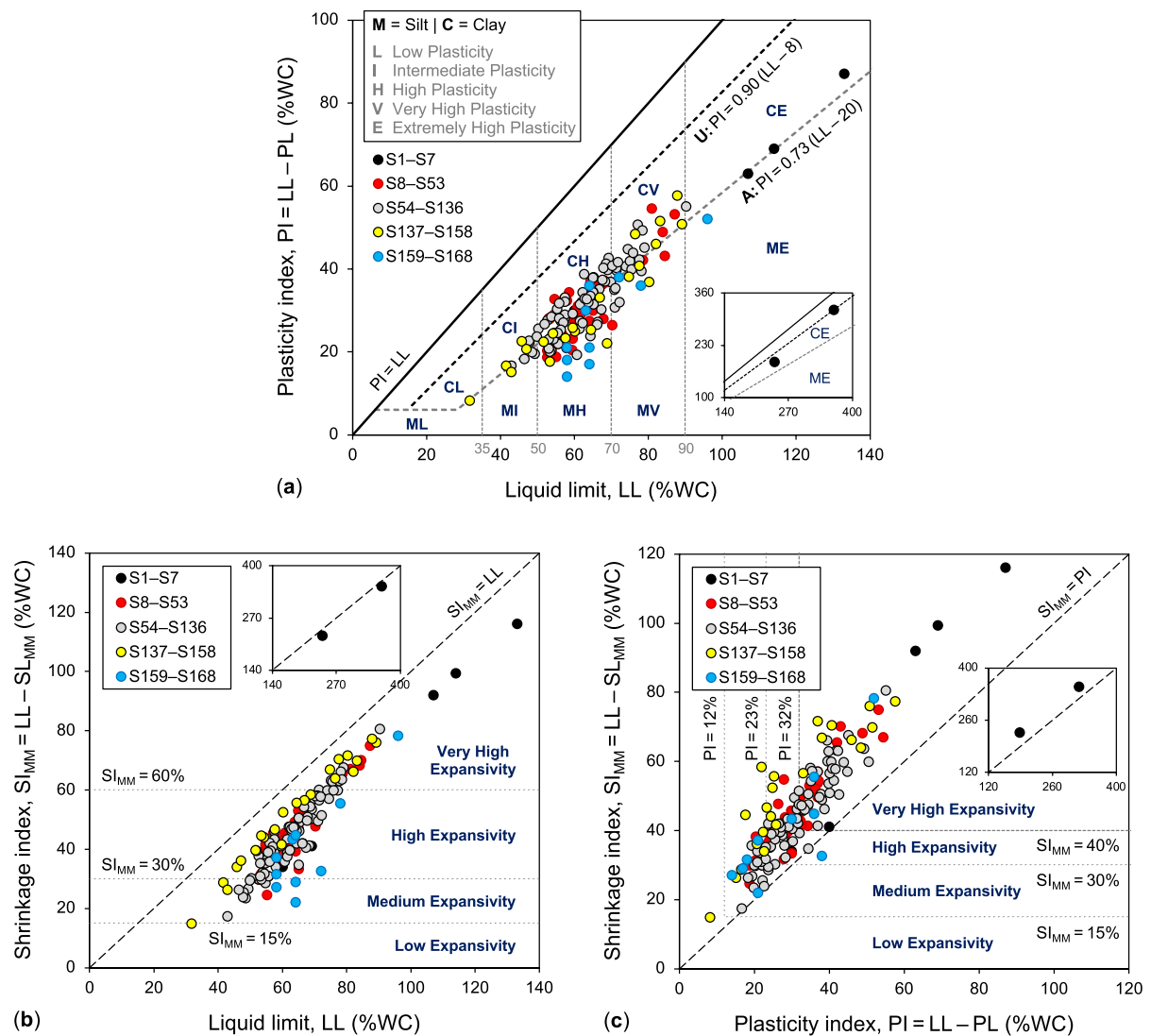


Fig. 2 Characteristics of the database soils ($N_s=168$): **a** Classification results based on the British-standard soil plasticity chart (BS 5930 2015); **b** Variations of SI_{MM}

(=LL - SL_{MM}) against LL (IS 1498 1970); **c** Variations of SI_{MM} (=LL - SL_{MM}) against PI (Raman 1967)

2 Database of SL_{MM} : SL_{WM} Test Results

A large and diverse database of SL_{MM} : SL_{WM} data pairs, pertaining to $N_s=168$ different fine-grained soil materials gathered from five different literature sources (Prakash et al. 2009; Kayabali 2011; Rehman et al. 2019; Özer and Yavuz 2021; Pratama et al. 2021), was assembled to assess the level of agreement between the MM and WM measurement methods (see Table 1). The compiled database includes a variety of soil types obtained from natural deposits across India, Indonesia and Turkey, as well as four commercially produced kaolin and bentonite materials. Furthermore, the database soils (herein designated as S_1 – S_{168}) account for reasonably wide ranges of soil index properties (gradation, plasticity and clay mineralogy)—that is, f_{clay} ($< 2 \mu m$) = 11–69%, f_{fines} ($< 75 \mu m$) = 30–100%, LL = 31.6–362.0 %WC, PI = 8.2–318.0 %WC, SL_{MM} = 7.1–42.0 %WC, $SI_{MM} = LL - SL_{MM}$ = 14.8–349.0 %WC, and $A_c = PI/f_{clay}$ = 0.39–2.23 (where f_{clay} , f_{fines} and A_c denote clay content, fines content and soil activity, respectively).

Referring to Fig. 2a, which illustrates the database soils plotted on the British-standard plasticity chart

(BS 5930 2015); all of the investigated soil materials plot below the U-Line (i.e., $PI = 0.9 \times (LL - 8)$), indicating that the database soils conform to the general correlation framework proposed by Casagrande (1947). In terms of classification (as per BS 5930 (2015)), the database consists of 78 silt and 90 clay soils, with the following classification frequencies (see Fig. 2a): $ML = 1$; $MI = 5$; $MH = 57$; $MV = 13$; $ME = 2$; $CL = 0$; $CI = 6$; $CH = 58$; $CV = 21$; and $CE = 5$. Finally, relevant soil-expansivity rankings for the database soils, obtained in accordance with the SI_{MM} -based classification frameworks suggested in the Indian standard IS 1498 (1970) and Raman (1967), are provided in Figs. 2b and 2c, respectively. It is noted that the SL (or SI) parameter is possibly not the most suitable index property for identifying/classifying expansive soils (Asuri and Keshavamurthy 2016; Prakash and Sridharan 2023); nevertheless, its adoption for this purpose is commonplace within the geotechnical engineering community (e.g., Yilmaz and Karacan 2002; Rao et al. 2011; Izdebska-Mucha and Wójcik 2022). Examining the suitability of different soil index properties for performing soil expansivity assessments is beyond the scope of the present study.

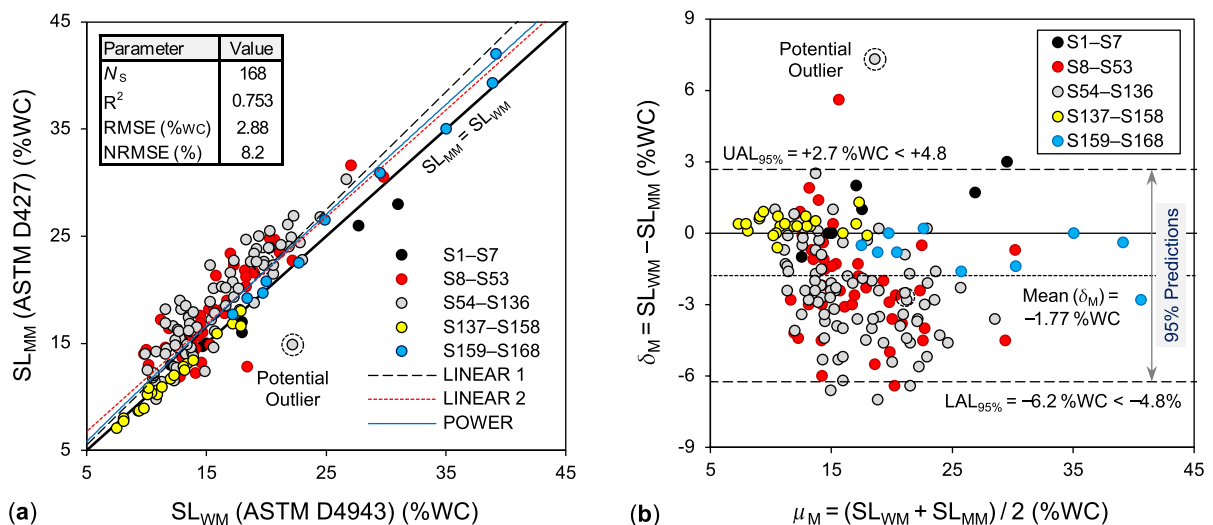


Fig. 3 Level of agreement between the SL_{MM} and SL_{WM} parameters for the database soils ($N_s=168$): **a** SL_{MM} : SL_{WM} correlation plot; **b** TMD residual plot. **Note:** LAL_{95%} and UAL_{95%} denote the 95% lower and upper statistical agreement limits, respectively

3 Results and Discussion

3.1 Statistical Appraisal of the SL_{MM} : SL_{WM} Relationship

Scatter plots illustrating the level of agreement between the MM and WM measurement methods for the database soils are presented in Fig. 3. Referring to the SL_{MM} : SL_{WM} correlation plot shown in Fig. 3a; the two SL measurement methods are strongly correlated (with $R^2=0.753$ for $N_S=168$); however, the data points mainly plot above the equality line of $SL_{MM}=SL_{WM}$, indicating that SL_{WM} generally underestimates the SL_{MM} parameter. Moreover, the root-mean-squared error (i.e., RMSE in %WC) and its normalized/dimensionless derivation (i.e., NRMSE expressed in terms of %) associated with the $SL_{MM}=SL_{WM}$ trendline, defined in Eqs. (2 and 3) (Soltani et al. 2018; Soltani and O’Kelly 2021a), were calculated as $RMSE=2.88$ %WC and $NRMSE=8.2\%$ (for $N_S=168$). These values, particularly the NRMSE being moderately higher than the desirable 5% reference limit (Soltani and O’Kelly 2021b, 2022), suggest that the MM and WM measurement methods do not produce identical SL values for a given fine-grained soil examined under similar testing conditions.

$$RMSE = \sqrt{\frac{1}{N_S} \sum_{m=1}^{N_S} \left(SL_{MM}^{(m)} - SL_{WM}^{(m)} \right)^2} \quad (2)$$

$$NRMSE = \frac{RMSE}{SL_{MM(max)} - SL_{MM(min)}} \times 100\% \quad (3)$$

where $SL_{MM(max)}$ and $SL_{MM(min)}$ =maximum and minimum of the SL_{MM} data, respectively; (m) =summation index; and N_S =number of soil materials (or SL_{MM} : SL_{WM} data pairs) investigated (here $N_S=168$).

To better understand the implications of employing the SL_{WM} parameter (over SL_{MM}) in routine geotechnical engineering practice, particularly its adoption in the many well-established empirical correlations that make use of SL_{MM} to estimate other important geotechnical design parameters (e.g., Sridharan and Nagaraj 2000, 2004, 2005; Yukselen-Aksoy et al. 2008; Vinod and Bindu 2010; Shimobe and Spagnoli 2022), the 95% lower and upper statistical agreement limits (i.e., $LAL_{95\%}$ and $UAL_{95\%}$, respectively; both

in %WC) between the WM and MM measurement methods were quantified and critically examined. Following the Tukey Mean–Difference (TMD) plotting technique, the $LAL_{95\%}$ and $UAL_{95\%}$ parameters for the database soils can be obtained as follows (Bland and Altman 1999):

$$LAL_{95\%} = \mu[\delta_M] - 1.96 \times \sigma[\delta_M] \quad (4)$$

$$UAL_{95\%} = \mu[\delta_M] + 1.96 \times \sigma[\delta_M] \quad (5)$$

where $\mu[\delta_M]$ and $\sigma[\delta_M]$ =arithmetic mean and standard deviation of the $\delta_M=SL_{WM} - SL_{MM}$ data (both in %WC), respectively.

In assessing the desirability of the $LAL_{95\%}$ and $UAL_{95\%}$ values, their magnitudes must be compared against a user-defined reference limit, here chosen as the highest acceptable water content difference in the MM measurement technique based on its repeatability (Rehman et al. 2020; Soltani and O’Kelly 2021a; Soltani et al. 2023). For a given fine-grained soil, the acceptable variation in the SL_{MM} parameter can be as high as ± 4.8 %WC (ASTM D427 2004); accordingly, this value was selected as the reference limit to assess the desirability of the $LAL_{95\%}$ and $UAL_{95\%}$ values. Referring to the TMD plot shown in Fig. 3b for the database soils ($N_S=168$); the mean of differences (between SL_{WM} and SL_{MM}) was calculated as $\mu[\delta_M]=-1.77$ %WC, indicating that the WM measurement method, on average, underestimated the SL_{MM} parameter by 1.77 %WC. The water content agreement limits were obtained as $LAL_{95\%}=-6.2$ %WC and $UAL_{95\%}=+2.7$ %WC, suggesting that 95% of the differences between the investigated SL_{WM} : SL_{MM} data lie between these two limits; the former being greater (in terms of magnitude) than the allowable reference limit of 4.8 %WC. These results further reinforce the notion that the WM measurement method generally underestimates the SL_{MM} parameter—that is, out of the 168 soil materials in the database, 124 soils produced $SL_{WM}<SL_{MM}$, 6 cases provided equal SL measurements, while 38 soils produced $SL_{WM}>SL_{MM}$; this implies that the likelihood of SL_{MM} -underestimation is 74%.

To investigate whether the discrepancy between the SL_{WM} and SL_{MM} parameters is related to fundamental soil properties (i.e., gradation, plasticity, soil type and/or clay mineralogy), the SL_{WM} -to- SL_{MM} ratio was plotted against the following parameters: (i) LL and

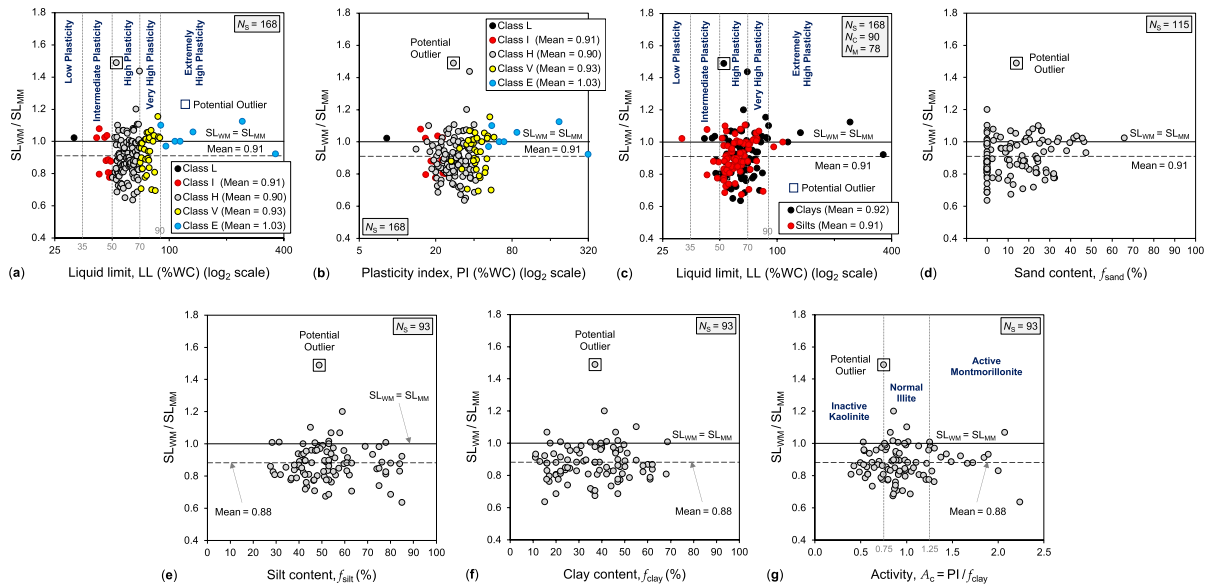


Fig. 4 Variations of the SL_{WM} -to- SL_{MM} ratio against fundamental soil properties for the compiled database: **a** LL (i.e., British-standard soil plasticity-level class); **b** PI; **c** LL (i.e., soil type (clay or silt)); **d** Sand ($> 75 \mu m$) content f_{sand} ; **e** Silt ($2-75 \mu m$) content f_{silt} ; **f** Clay ($< 2 \mu m$) content f_{clay} ; **g** Activity

$A_c = PI/f_{clay}$. **Note:** Classes L, I, H, V and E (in Figs. 4a and 4b) denote the British-standard *low*, *intermediate*, *high*, *very high* and *extremely high* soil plasticity-level classes, respectively; and N_C and N_M (in Fig. 4c) denote the number of clays and silts, respectively

PI (see Figs. 4a–c); (ii) sand, silt and clay contents (see Figs. 4d–f); and (iii) activity A_c (see Fig. 4g). As is evident from Fig. 4, the SL_{WM} -to- SL_{MM} ratio (with an average value of 0.91 for $N_S = 168$) does not exhibit any specific trend (e.g., increasing or decreasing) with changes in soil type or behavior for the database soils investigated. In view of the above, one can postulate that the differences between the SL_{WM} and SL_{MM} parameters are likely systematic in nature, arising from the differences between the materials (mercury versus wax) and testing methodologies, and their associated potential experimental errors, involved in undertaking soil-volume measurements using these two approaches.

Since the differences between the WM and MM measurement methods are mostly systematic, one should be able to deduce the SL_{MM} parameter as a function of SL_{WM} (i.e., $SL_{MM} = F(SL_{WM})$) with reasonable accuracy. Employing the conventional least-squares optimization method, the following linear and power relationships can be derived for the database soils (see the three trendlines in Fig. 3a for $N_S = 168$):

$$SL_{MM} = 1.100 \times SL_{WM} \quad (6)$$

$$SL_{MM} = 1.002 \times SL_{WM} + 1.747 \quad (7)$$

$$SL_{MM} = 1.256 \times SL_{WM}^{0.954} \quad (8)$$

Relevant statistical fit-measure indices showing the level of agreement between Eqs. (6–8) and the actual SL_{MM} parameter are presented in Table 2. The $LAL_{95\%}$ and $UAL_{95\%}$ limits for these equations were found to be symmetrical; they were, respectively, obtained as -4.7 and $+4.4$ %WC for Eq. (6), -4.5 and $+4.5$ %WC for Eq. (7), and -4.6 and $+4.3$ %WC for Eq. (8). Given that these water content agreement limits are all lower (in terms of magnitude) than the 4.8 %WC reference limit, the SL_{MM} values deduced by the proposed $SL_{MM} = F(SL_{WM})$ relationships can be deemed acceptable. Accordingly, when attempting to input SL_{WM} in an SL_{MM} -based empirical correlation to predict other geotechnical design parameters, these relationships (particularly Eqs. (7) and (8)) can be employed to minimize systematic prediction errors. Table 2 also provides a detailed comparison between other $SL_{MM} = F(SL_{WM})$ relationships reported in the research literature (by Kayabali (2013), Rehman et al. (2019)

Table 2 Level of agreement between the SL_{WM} and SL_{MM} parameters

Source	Calibration details					Performance metrics for the present database ($N_S=168$)				
	N_S	LL (%WC)	PI (%WC)	SL _{MM} (%WC)	Relationship	R^2	RMSE (%WC)	NRMSE (%)	LAL _{95%} (%WC)	UAL _{95%} (%WC)
Present study	168	31.6–362.0	8.2–318.0	7.1–42.0	SL _{MM} = SL _{WM}	0.753	2.88	8.2	−6.2 R	+2.7 A
Present study	168	31.6–362.0	8.2–318.0	7.1–42.0	(6) SL _{MM} = 1.100 × SL _{WM}	0.838	2.33	6.7	−4.7 A	+4.4 A
Present study	168	31.6–362.0	8.2–318.0	7.1–42.0	(7) SL _{MM} = 1.002 × SL _{WM} + 1.747	0.847	2.27	6.5	−4.5 A	+4.5 A
Present study	168	31.6–362.0	8.2–318.0	7.1–42.0	(8) SL _{MM} = 1.256 × SL _{WM} ^{0.954}	0.846	2.27	6.5	−4.6 A	+4.3 A
Kayabali (2013)	120	42.9–90.3	16.7–55.1	9.8–31.6	(9) SL _{MM} = 1.250 × SL _{WM} − 1.625	0.784	2.69	7.7	−4.5 A	+5.8 R
Rehman et al. (2019)	83	42.9–90.3	16.7–55.1	9.8–30.3	(10) SL _{MM} = 1.010 × SL _{WM} + 2.230	0.836	2.35	6.7	−3.8 A	+5.1 R
Özer and Yavuz (2021)	22	31.6–89.1	8.2–57.7	7.1–18.0	(11) SL _{MM} = 0.986 × SL _{WM} − 0.181	0.704	3.15	9.0	−6.6 R	+2.3 A

N_S , number of soil materials (or SL_{MM}:SL_{WM} data pairs) investigated; %WC percent water content; **A** and **R** = acceptable and unacceptable agreement limits, respectively

N_S , number of soil materials (or SL_{MM} : SL_{WM} data pairs) investigated; %WC percent water content; ^A and ^R = acceptable and unacceptable agreement limits, respectively

and Özer and Yavuz (2021), as given in Eqs. (9–11), respectively) and those proposed in the present investigation (Eqs. (6–8)). Mindful of the NRMSE, LAL_{95%} and UAL_{95%} values presented in this table, the relationships derived in this study, particularly Eqs. (7 and 8), outperform those proposed in earlier investigations.

$$SL_{MM} = 1.250 \times SL_{WM} - 1.625 \quad (9)$$

$$SL_{MM} = 1.010 \times SL_{WM} + 2.230 \quad (10)$$

$$SL_{MM} = 0.986 \times SL_{WM} - 0.181 \quad (11)$$

3.2 Soil Plasticity as a Proxy for SL_{MM} Estimation

Because of the challenges associated with the MM test, researchers and practitioners have long relied on (or even advocated for) empirical-type correlations to estimate the SL -state water content as a function of soil plasticity (e.g., Schultze and Muhs 1967; Holtz et al. 2011; Wijaya et al. 2015; Torfi et al. 2021; Alotaibi et al. 2022). The most commonly practiced/accepted approach in this context seems to be the Casagrande (1932) graphical construction (still appearing in many soil mechanics textbooks), which can be formalized as follows (Budhu 2011):

$$SL_P = PI_{UA} \times \left(\frac{LL + LL_{UA}}{PI + PI_{UA}} \right) - LL_{UA} \quad (12)$$

where SL_P =predicted SL_{MM} ; and LL_{UA} and PI_{UA} = LL and PI values at the intersection of the **U**: $PI=0.9 \times (LL - 8)$ and **A**: $PI=0.73 \times (LL - 20)$ lines, respectively (i.e., $LL_{UA} = -43.53\%$ and $PI_{UA} = -46.38\%$).

Note that in assessing the predictive performance of Eq. (12), only those datasets having LL magnitudes definitively obtained based on equivalent testing standards were considered (i.e., S_8 – S_{158} ($N_S=151$), with the LL and PL parameters both measured explicitly in accordance with ASTM D4318 (2000, 2017); see Table 1). This was to eliminate systematic variations in the LL and PI ($=LL - PL$) parameters arising from differences between the mechanics of the percussion-cup and fall-cone devices employed for LL -determination (O’Kelly et al. 2018; O’Kelly and Soltani 2022). In other words, it is well established that for the percussion-cup and fall-cone LL

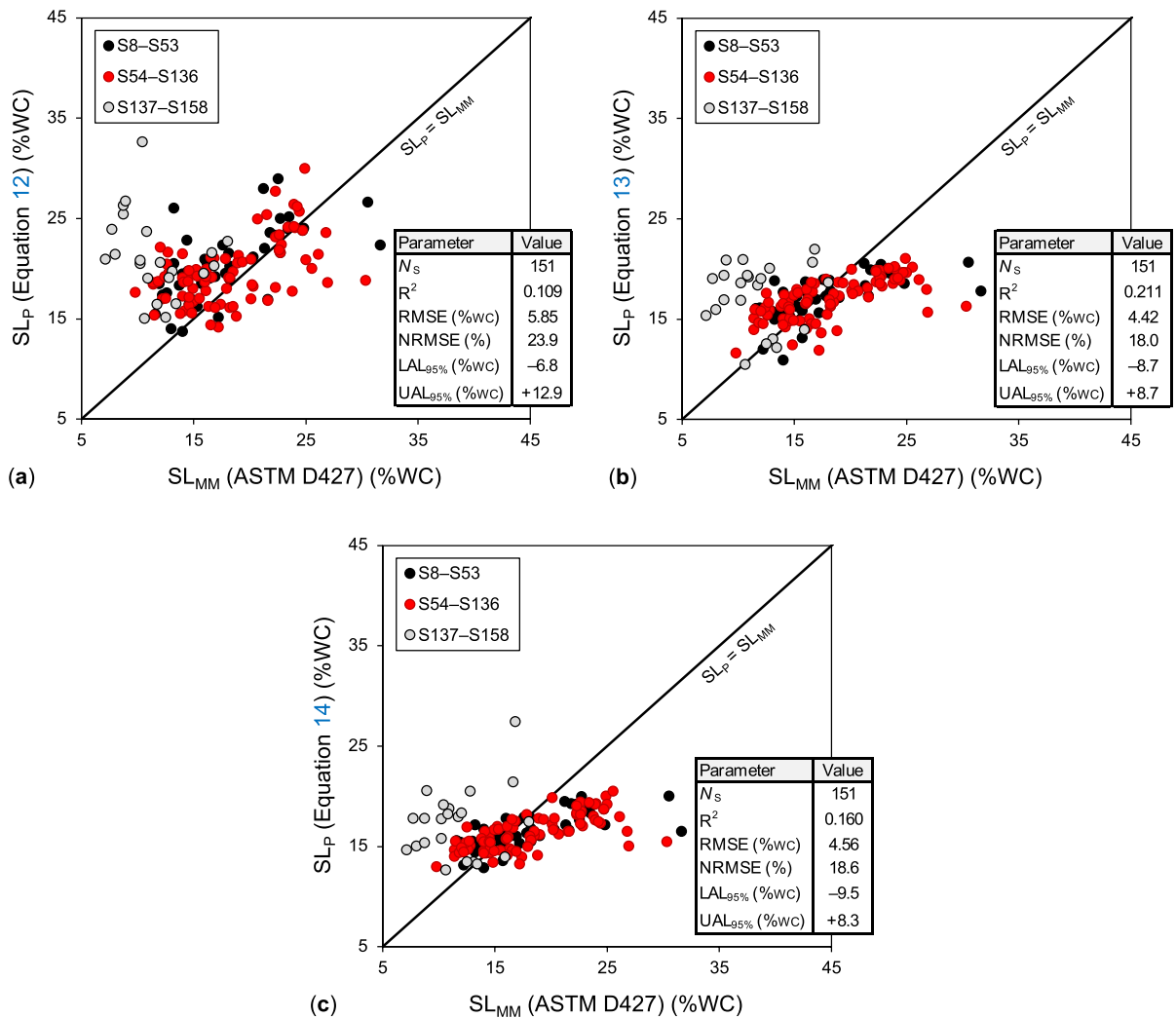


Fig. 5 Variations of SL_p (deduced empirically by the LL and PI) against SL_{MM} for the database soils ($N_s = 151$): **a** Eq. (12) (Casagrande 1932); **b** Eq. (13); **c** Eq. (14)

Table 3 Level of agreement between the SL_p (deduced empirically by LL and PI) and SL_{MM} parameters ($N_s = 151$)

Correlation	R^2	RMSE (%WC)	NRMSE (%)	$LAL_{95\%}$ (%WC)	$UAL_{95\%}$ (%WC)
(12) $SL_p = PI_{UA} \times \left(\frac{LL + LL_{UA}}{PI + PI_{UA}} \right) - LL_{UA}$	0.109	5.85	23.9	-6.8 ^R	+12.9 ^R
(13) $SL_p = 0.101 \times LL - 0.346 \times PI + 21.616$	0.211	4.42	18.0	-8.7 ^R	+8.7 ^R
(14) $SL_p = 47.086 \times LL^{0.125} \times PI^{-0.462}$	0.160	4.56	18.6	-9.5 ^R	+8.3 ^R

%WC, percent water content; LL_{UA} and PI_{UA} = LL and PI values at the intersection of the U: $PI = 0.9 \times (LL - 8)$ and A: $PI = 0.73 \times (LL - 20)$ lines (i.e., $LL_{UA} = -43.53\%$ and $PI_{UA} = -46.38\%$); ^R = unacceptable agreement limit

methods, significant differences in their measured values occur for extremely high plasticity soils having $LL > \sim 100$ – 120 %WC (O’Kelly et al. 2018).

The predictive performance of Eq. (12) is demonstrated in Fig. 5a and Table 3. Aside from the poor correlation (with $R^2 = 0.109$ for $N_s = 151$) and high

NRMSE value of 23.9%, the $LAL_{95\%} = -6.8\%WC$ and $UAL_{95\%} = +12.9\%WC$ values were found to be significantly greater (in terms of magnitude) than the allowable 4.8 %WC reference limit, indicating that the Casagrande graphical method, at best, can only provide a rough approximation of the actual SL_{MM} parameter. As a further refinement, it was decided to investigate the possibility of improving the predictions through multiple regression analysis; this endeavor produced the following correlations (for $N_s = 151$):

$$SL_P = 0.101 \times LL - 0.346 \times PI + 21.616 \quad (13)$$

$$SL_P = 47.086 \times LL^{0.125} \times PI^{-0.462} \quad (14)$$

The predictive performance of Eqs. (13 and 14) is demonstrated in Figs. 5b and 5c (and also summarized in Table 3), respectively. Although the new predictions appear to slightly outperform those produced by Eq. (12), they are still equally unsatisfactory, with both correlations producing significantly higher $LAL_{95\%}$ and $UAL_{95\%}$ magnitudes than 4.8 %WC (i.e., $LAL_{95\%} = -8.7\%WC$ and $UAL_{95\%} = +8.7\%WC$ for Eq. (13), and $LAL_{95\%} = -9.5\%WC$ and $UAL_{95\%} = +8.3\%WC$ for Eq. (14)). These results would indicate that the SL-state water content is not governed by soil plasticity. As such, when the SL parameter is desired, WM-testing or any other non-standardized alternative that directly and reliably measures the soil shrinkage factors (e.g., Cerato and Lutenegeger 2006; Prakash et al. 2011; Prakash and Sridharan 2012; Fredlund and Houston 2013; Hobbs et al. 2014, 2019; Li and Zhang 2019; Deka et al. 2021; Barman and Mishra 2022; Dias et al. 2023) should be retained. In their experimental investigations, Sridharan and Prakash (1998, 2000) demonstrated that the SL-state water content, which corresponds to the minimum void ratio during drying, is controlled primarily by the fine-grained soil's particle-size distribution and its inter-particle shear resistance. Consequently, fine-grained soils with more uniform/poor gradations (i.e., decrease in particle-packing capacity) and/or higher shear resistance at the particle level tend to mobilize higher SL values. Moreover, no satisfactory correlation exists between SL and the LL, PI and/or f_{clay} parameters (Sridharan and Prakash 1998). On the other hand, besides the initial water content of the soil test specimen

Table 4 Soil-expansivity rankings, based on the IS 1498 (1970) and Raman (1967) SI_{MM} -based classification frameworks, employing the SI_{WM} parameter

Relationship	IS 1498 (1970)					Raman (1967)				
	N_s	N_D	CAL (%)	Corrected N_D^A	Corrected CAL (%) ^A	N_s	N_D	CAL (%)	Corrected N_D^A	Corrected CAL (%) ^A
(15) $SI = LL - SL_{WM}$	168	14	92	1	99	168	4	98	1	99
(16) $SI = LL - (1.002 \times SL_{WM} + 1.747)$	168	8	95	1	99	168	5	97	1	99
(17) $SI = LL - (1.256 \times SL_{WM}^{0.954})$	168	8	95	1	99	168	5	97	2	99

N_s , number of soil materials (or SI_{MM} - SI_{WM} data pairs) investigated; N_D , number of classification discrepancies; CAL, classification agreement level (i.e., $CAL = (N_s - N_D)/N_s \times 100\%$); ^A = corrected N_D and CAL with consideration of possible errors associated with the standard SL_{MM} (and hence SI_{MM}) measurements

undergoing drying, the clay content and its associated mineralogical activity are the primary drivers of shrinkage potential. In other words, fine-grained soils containing greater clay content of higher mineralogical activity generally exhibit higher volumetric/linear shrinkage strains (Izdebska-Mucha and Wójcik 2013). These shrinkage potential drivers also serve as proxies for plasticity in inorganic fine-grained soils, with greater clay contents of higher activity typically associated with higher plasticity levels. In view of all the above, compared to the SL parameter that is governed primarily by soil gradation and inter-particle shear resistance (rather than clay content/mineralogy), it would be reasonable to expect relatively stronger correlations between the volumetric/linear shrinkage strain and the LL, PI and/or f_{clay} parameters. Such correlations are reported in Izdebska-Mucha and Wójcik (2013) and Soltani et al. (2023) for volumetric and linear shrinkage, respectively.

3.3 Use of SL_{WM} in Existing SL_{MM} -Based Classification Approaches for Soil Expansivity Assessments

Although not credited as the most suitable soil index property for identifying/classifying expansive soils, the SL_{MM} parameter, often in conjunction with the LL and/or PI, has been routinely employed to perform preliminary soil expansivity assessments (e.g., Altmeyer 1955; Holtz 1959; Ranganatham and Satyanarayan 1965; Raman 1967; IS 1498 1970; Sowers and Sowers 1970; Dakshanamurthy and Raman 1973). Accordingly, adopting this approach, any alternate SL_{MM} measurement method, such as the WM technique, is expected to produce the same expansivity rankings as deduced based on the SL_{MM} method. To the authors' knowledge, this requirement has not yet been examined (nor discussed) for the SL_{WM} parameter. Herein, an attempt is made to examine the validity of SL_{WM} , as well as Eqs. (7 and 8), in performing soil expansivity assessments based on the IS 1498 (1970) and Raman (1967) SI_{MM} -based (i.e., $SI_{MM} = LL - SL_{MM}$) classification frameworks. For a complete review of the many existing inferential testing methods proposed for assessing

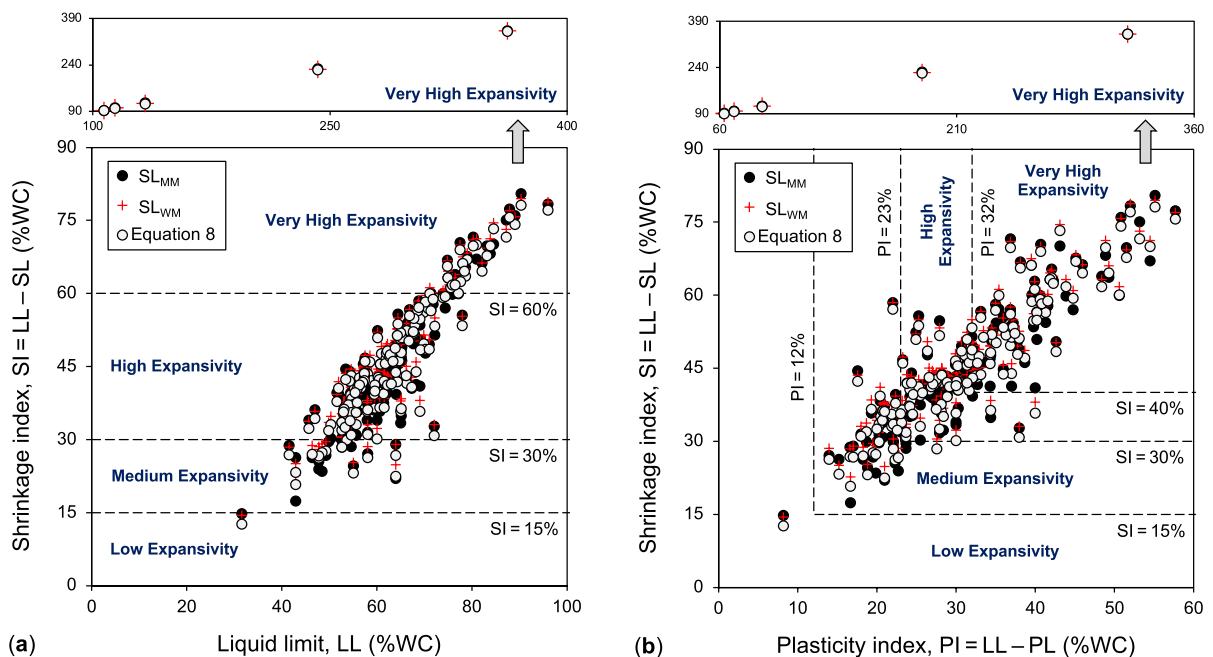


Fig. 6 Validity of the SL_{WM} parameter and Eq. (8) in performing soil expansivity assessments based on the **a** IS 1498 (1970) and **b** Raman (1967) SI_{MM} -based classification frameworks

soil expansivity, the reader is referred to the paper by Asuri and Keshavamurthy (2016).

Following the IS 1498 (1970) classification framework, employing the WM-deduced SI (i.e., $SI_{WM} = LL - SL_{WM}$), a total of $N_D = 14$ cases (out of $N_S = 168$ examined) were found to produce dissimilar soil-expansivity classes when compared to those deduced using the SI_{MM} parameter. This implies an overall classification agreement level (i.e., $CAL = (N_S - N_D)/N_S \times 100\%$) of 92%. However, when employing the SL obtained from Eqs. (7 and 8), the CAL can be improved to 95% ($N_D = 8$) (see Table 4 and Fig. 6a). Concerning the Raman (1967) framework, which employs both the SI_{MM} and PI parameters to assign soil-expansivity rankings; the likelihood of achieving the same classifications was found to be 98% ($N_D = 4$) when employing SI_{WM} in lieu of the SI_{MM} parameter, and 97% ($N_D = 5$) for applying both Eqs. (7 and 8) (see Table 4 and Fig. 6b). Although promising, if the acceptable errors associated with the standard SL_{MM} (and hence SI_{MM}) measurements are also considered in the classification analysis, some of the misclassifications may become passable. To examine this prospect, classification discrepancies satisfying $|SI_{MM} - SI| \leq 4.8\% \text{ WC}$ (where SI is given by Eqs. (15–17) outlined in Table 4) were tentatively deemed to be acceptable. It should be reminded that 4.8 %WC represents the highest acceptable variation/error in the SL_{MM} and hence SI_{MM} parameters, as recommended/allowed by ASTM D427 (2004). Following this modification, the CAL can be improved to 99% for all cases (see Table 4). In view of all the above, one can conclude that the same soil-expansivity rankings can be directly achieved using the SL_{WM} and hence SI_{WM} parameters (in lieu of SL_{MM} and SI_{MM}) and without the need of implementing $SL_{WM} \rightarrow SL_{MM}$ conversion relationships (e.g., Eqs. (7 and 8). This viewpoint is further supported by the fact that common classification frameworks for expansive soils invariably assign expansivity rankings based on broad SI or SI:PI domains (rather than fixed SI or SI:PI values), thereby permitting some level of deviation from the SL_{MM} parameter (when using SL_{WM} as its replacement) to still be acceptable towards producing identical soil-expansivity rankings.

4 Summary and Conclusions

Because of the hazards associated with handling mercury, most standards organizations have withdrawn the conventional mercury (displacement) method (MM) for shrinkage limit (SL) determination of fine-grained soils. To foster more widespread use of the wax (coating) method (WM) for SL determination, this study re-examined the level of agreement between the MM- and WM-deduced SL parameters (i.e., SL_{MM} and SL_{WM} , respectively). Following comprehensive statistical analyses performed using the largest and most diverse database of its kind, to date, consisting of SL_{MM} – SL_{WM} measurements for 168 different fine-grained soil materials (covering liquid limit (LL) = 31.6–362.0 %WC, plasticity index (PI) = 8.2–318.0 %WC and SL_{MM} = 7.1–42.0 %WC), the following conclusions can be drawn:

The MM and WM measurement methods do not produce identical SL values for a given fine-grained soil examined under similar testing conditions, with their discrepancy being systematic and hence likely arising from the differences between the materials (mercury versus wax) and testing methodologies, and their associated potential experimental errors, involved in undertaking soil-volume measurements using these two methods. The 95% lower and upper statistical agreement limits between the SL_{WM} and SL_{MM} parameters were obtained as $LAL_{95\%} = -6.2\% \text{ WC}$ and $UAL_{95\%} = +2.7\% \text{ WC}$; the former being greater (in terms of magnitude) than the allowable 4.8 %WC reference limit suggested in ASTM D427 (2004).

New $SL_{WM} \rightarrow SL_{MM}$ conversion relationships were established, allowing the SL_{MM} parameter to be deduced as a function of SL_{WM} with high accuracy (i.e., the $LAL_{95\%}$ and $UAL_{95\%}$ magnitudes for the newly proposed conversion equations were all lower than the allowable 4.8 %WC limit). Hence, when inputting the SL_{WM} parameter in an SL_{MM} -based empirical correlation to predict other geotechnical design parameters, the newly proposed conversion relationships can be employed to minimize systematic prediction errors.

The reliability of empirical-type correlations in estimating SL_{MM} as a function of soil plasticity (i.e., LL and PI) was also investigated. It was demonstrated that plasticity-based correlations, at

best, can only provide a rough approximation of the actual SL_{MM} parameter, with their $LAL_{95\%}$ and $UAL_{95\%}$ magnitudes being significantly higher than the allowable 4.8 %WC reference limit. Accordingly, when the SL parameter is desired, WM-testing or any other alternative method that directly and reliably measures the soil shrinkage factors should be retained.

Finally, an attempt, for the first time, was made to evaluate the SL_{WM} (in lieu of the SL_{MM}) parameter for obtaining preliminary soil expansivity assessments based on existing SL_{MM} -based classification systems. It was demonstrated that the same soil-expansivity rankings, as obtained for SL_{MM} results, are achieved using SL_{WM} measurements for the investigated fine-grained soils (i.e., without the need of applying $SL_{WM} \rightarrow SL_{MM}$ conversion equations).

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests.

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