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RESEARCH

Discussion: Utilizing Waste-Shredded Rubber Pieces for Improved Foundation Stability [Transp. Infrastruct. Geotech. 11(6), 3941–3968]

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Abstract

This communication article presents a discussion of various identified shortcomings in the original research paper by Thapa et al. (the Authors) that was recently published in Transp. Infrastruct. Geotech. 11(6), 3941–3968, 2024. The Authors investigated the application of waste shredded rubber pieces (SRPs) for improving the performance of shallow foundations bearing on a problematic collapsible soil obtained from the Western Uttar Pradesh region of India. They performed laboratory experiments, including Atterberg (consistency) limits, compaction, unconfined compressive strength and undrained direct-shear tests, on the unamended soil (i.e., 0% SRP content) and five soil–SRP blends prepared with gravimetric SRP contents ranging from 1% to 5%. Moreover, the Authors employed finite-element method (FEM) modeling to assess the effects of SRP content on the ultimate bearing capacity (*B*) and settlement (*S*) response of an infinite strip footing bearing on the investigated compacted soil–SRP blends. Using the results obtained from the six FEM simulations, the Authors then produced multiple linear regression (MLR) models for predicting the FEM-generated *B* and *S* values of the compacted soil amended with 0–5% SRP additive. In this communication article, the Discussers raise several shortcomings of the Authors' research, including (**i**) the presented Atterberg limits results are fundamentally compromised by the inclusion of the coarse SRP additive in the test material, and (**ii**) the validity and applicability of their proposed MLR models for predicting the *B* and *S* responses of shallow footings bearing on the SRP-amended soil.

Keywords Soil improvement · Shredded rubber pieces · Atterberg limits · Shallow foundation · Multiple regression

Abbreviations

ASTM	American Society for Testing and Materials
BS	British Standard

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FEM	Finite-element method
IS	Indian Standard
MLR	Multiple linear regression
RMFGS	Rubber-mixed fine-grained soil
SRP	Shredded rubber piece

Notations

B	Ultimate bearing capacity
c	Undrained (apparent) cohesion
G_s^S	Specific gravity of soil solids
G_s^{SRP}	Specific gravity of SRPs
LL	Liquid limit
MAPE	Mean absolute percentage error
NRMSE	Normalized root mean squared error
PI	Plasticity index (=LL – PL)
PL	Plastic limit
R^2	Coefficient of determination
RMSE	Root mean squared error
S	Settlement (at ultimate limit state)
UCS	Unconfined compressive strength
ϕ	Undrained friction angle

1 Introduction

This communication article presents a discussion of the original research reported in the paper by Thapa et al. (2024) (hereafter referred to as the Authors), which investigated the application of waste shredded rubber pieces (SRPs) for improving the bearing performance of shallow foundations resting on a problematic collapsible soil obtained from the Western Uttar Pradesh region of India. Laboratory experiments, including Atterberg/consistency limits, compaction, unconfined compressive strength (UCS) and undrained direct-shear tests, were conducted on the unamended soil (i.e., 0% SRP content) and five soil–SRP blends prepared with gravimetric SRP contents ranging from 1% to 5%, giving a total of six experimental data points for each testing scenario investigated. Additionally, the Authors employed finite-element method (FEM) modeling to evaluate the effects of varying the SRP content (in the range of 0–5%) on the ultimate bearing capacity (B in kPa) and settlement (S in mm) response of the compacted unamended and SRP-amended soil for the specific scenario of an infinite strip footing resting on the ground surface. Using the results obtained from these six FEM simulations, the Authors then produced multiple linear regression (MLR) models to predict the FEM-deduced B and S values of the compacted soil amended with between 0% and 5% SRP additive. Overall, the Authors' efforts in fostering sustainable soil stabilization practices are commendable and gratefully acknowledged.

In this communication article, the Discussers present some observations on (**i**) the Authors' Atterberg limits testing approach, which fundamentally compromises the validity of their liquid limit (LL), plastic limit (PL) and plasticity index (PI = LL − PL) results in the context of SRP inclusion, and (**ii**) their proposed MLR models for *B* and *S* predictions concerning shallow foundations bearing on the compacted soil–SRP blends. It should be mentioned that the Authors did not report any experimental testing to directly measure the *B* and *S* parameters; these were entirely derived from FEM simulations. In other words, the Authors' MLR models were not validated using FEM (or any other approach), as they were solely developed to predict the six FEM-generated data.

2 Atterberg Limits Determinations for Soil–SRP Blends

Standard protocols for Atterberg limits testing—including IS 2720–5 (1985) of the Bureau of Indian Standards used by the Authors, and also the British, American and Australian Standards (BS 1377–2 1990; ASTM D4318 2017; AS 1289.3.1.1 2009; AS 1289.3.2.1 2009)—exclusively investigate the fraction of the geomaterial that passes the #40 sieve designation, which encompasses particles equivalent to *clay* (< 2 μm), *silt* (2–75 μm) and *fine sand* (75–425 μm) particle size ranges. As such, the Atterberg limits testing performed by the Authors for the soil–SRP mixtures should singularly investigate the fraction of each soil–SRP blend that is finer than 0.425 mm. However, referring to Fig. 1 of the Authors' paper, the particle-size distribution of the SRP material that was added to the test soil ranged between approximately 0.6 and 5.0 mm. Accordingly, the Atterberg (soil consistency) limits framework and its standard testing procedures for LL, PL and PI determinations should strictly not be adopted in the case of the 1–5% SRP-mixed soil samples of the Authors' investigation. It should be noted that the 1–5% gravimetric SRP contents examined in the Authors' study would be equivalent to volumetric SRP fractions of about 3–15% ($\approx$ 1–5% $\times G_s^S / G_s^{SRP}$, where G_s^S and G_s^{SRP} denote the specific gravities of the soil solids and SRP particles, respectively, with values of $G_s^S = 2.57$ and $G_s^{SRP} = 0.86$ reported in the Authors' paper). Accordingly, with up to 15% by volume of the soil–SRP blends comprised of individual SRPs ranging between 0.6 and 5.0 mm in size (i.e., each SRP substantially greater than the 0.425-mm maximum particle size requirement), it is considered that the LL, PL and PI results reported by the Authors for their investigated SRP-mixed soil samples have limited practical/physical meaning in terms of conventional Atterberg (consistency) limits indices.

It is worth mentioning here that an increasing number of published studies (e.g., Seda et al. 2007; Trouzine et al. 2012; Srivastava et al. 2014; Basson and Ayothiraman 2020; Ayothiraman et al. 2022; Omer et al. 2022; Anglaaere et al. 2024; Raj et al. 2024) focused on blending fine-grained soils with granular or fibrous additives (for soil stabilization purposes) have also overlooked the fundamental 'finer than 0.425-mm particle size' requirement set out in the sample preparation procedure for performing Atterberg limits testing. Like the Authors' paper under discussion, the inclusion of significant volumetric fractions of coarser than 0.425-mm particle size materials in these experimental studies diminishes the practical/physical meaning of their reported Atterberg (consistency) limits results. Whereas examples of technically sound investigations reporting on the Atterberg limits of rubber-mixed fine-grained soil (RMFGS) materials include the studies in Cetin et al. (2006), Akbarimehr and Aflaki (2018) and Soltani et al. (2019), where any rubber particles larger than 0.425 mm (if present) were removed from the Atterberg limits samples before performing the LL and PL tests.

It is the Discussers' viewpoint that the Authors' observed changes in the LL, PL and PI parameters measured for the soil–SRP blends are an artifact of the non-compliance with standard protocols for Atterberg limits testing (i.e., which require the exclusion of any constituent particles larger than 0.425-mm in size). For instance, with w_L% denoting the gravimetric water content value corresponding to the LL state transition, in discussing their Atterberg limits results, the Authors assert that "… the change in w_L% reveals that the addition of SRP has generally increased the soil's cohesiveness and reduced its susceptibility to liquid flow …". This interpretation is fundamentally inconsistent with basic soil mechanics principles. Firstly, the SRPs do not exhibit water-induced plasticity, and they possess significantly lower specific surface area and negligible water adsorption–retention capacity compared to the fine-grained soil solids (Cetin et al. 2006; Soltani et al. 2019). Accordingly, contrary to the Authors' stated assertion, the presence of the SRPs in the soil matrix is expected to reduce the overall cohesive character of the tested soil. Furthermore, akin to that observed when artificially increasing the fine sand (75–425 μm) content in fine-grained soils (e.g., Jyothi et al. 2020), the experimental studies reported by Cetin et al. (2006), Akbarimehr and Aflaki (2018) and Soltani et al. (2019) indicate that the LL parameter for RMFGS materials tested in full accordance with Atterberg limits testing standards generally exhibits a decreasing trend with increasing rubber additive content. Whereas, referring to Fig. 4 or Table 4 of the Authors' paper, compared to the unamended soil, the LL parameter for the Authors' soil–SRP blends shows an overall increase of 9% to 23% as the SRP content increases from 1% to 3%, respectively, followed by a marginal decrease of 6% to 9% for SRP contents of 4% and 5%. The most obvious anomaly, however, occurs for the Authors' PL results. The international testing standards, including IS 2720–5 (1985) adopted by the Authors, define Atterberg's PL as the lowest water content for which a uniform thread (formed from the fraction of the geomaterial passing the #40 sieve) first begins to crumble when manually rolled out on a glass plate to about 3.0 mm in diameter. Given that the sizes of the individual particles comprising the SRP material ranged up to 5.0 mm, firstly it would not be possible to form a uniform 3.0-mm-diameter soil–SRP thread by rolling action in order to define the end condition of the PL test. Consequently, it would not be possible to experimentally establish a PL state (i.e., the value of the PL parameter) for the investigated soil–SRP blends. Additionally, rubber particles lack water-induced plasticity, such that increasing the rubber content (< 425-mm sized) in RMFGS materials causes a progressive decrease in the PL value. However, referring to Fig. 4 or Table 4 of the Authors' paper, compared to the unamended soil, the PL parameter for the Authors' soil–SRP blends shows an overall increase of 15% to 49% as the SRP content increases from 1% to 5%, respectively. Finally, for more detailed discussions on the mechanisms governing other geotechnical properties of RMFGS materials, such as their stress–strain response (i.e., rubber-induced arching effects, mismatch in relative stiffness between soil–rubber and individual soil agglomerations, and rubber-induced frictional resistance), the reader could refer to the papers by Soltani et al. (2021, 2022a).

3 Regression Models for Predicting Bearing Capacity and Settlement of Compacted Soil–SRP Blends

Using six FEM-generated maximum bearing capacity (B) and settlement (S) data pairs (i.e., obtained for the compacted unamended soil and five investigated soil–SRP blends prepared with 1–5% SRP content), the Authors developed MLR models to predict the maximum B (in kPa) and S (in mm) responses of soil–SRP blends. These MLR models were given by Eqs. 1 and 2 in the Authors' paper and are reproduced below using the same equation numbering:

$$S = -92.40 - 0.82 \times \text{SRP} + 75.12 \times \text{UCS} + 6.93 \times c + 4.09 \times \phi \tag{1}$$

$$B = -606.05 - 2.33 \times \text{SRP} + 122.08 \times \text{UCS} + 13.67 \times c + 27.64 \times \phi \tag{2}$$

In developing these MLR models, the Authors employed as the modeling inputs (or independent variables) the SRP content (in %), along with the blends' undrained cohesion and friction angle (i.e., c in kg/cm^2 and ϕ in degrees, obtained via direct-shear testing), and the UCS parameter (in kg/cm^2). Apart from the Authors' not reporting any routine statistical fit-measure indices (e.g., R^2, RMSE, NRMSE and MAPE) necessary to evaluate the predictive performance of the proposed data-driven MLR models (e.g., Baghbani et al. 2023; Teodosio et al. 2023; Akis and Cigdem 2024), the Discussers have identified several issues that could undermine the overall validity/applicability of the Authors' Eqs. 1 and 2, as elaborated below.

- Using only six data points in fitting an MLR model with five regression coefficients, as done in the Authors' study for developing Eqs. 1 and 2 (see the Authors' Table 7), is inherently problematic. This 6:5 setup is bound to produce an artificially high R^2 value (regardless of whether the chosen input parameters are physically relevant, appropriately representative and independent, and/or statistically meaningful); however, such an outcome is statistically unreliable and indicative of overfitting (Draper and Smith 1998). To minimize overfitting effects and ensure model reliability and generalizability, the ratio of the sample (data) size to the number of regressor coefficients should be substantially greater than the 6:5 (=1.2) ratio adopted in the Authors' investigation (Burmeister and Aitken 2012).
- As their name implies, the independent variables used in regression modeling should (normally) be independent of each other. Hence, the inclusion of SRP content (in Eqs. 1 and 2) as an independent variable alongside the UCS, c and ϕ parameters can be problematic, as the values of these strength parameters are inherently functions of the SRP content for the investigated soil–SRP blends (e.g., see Fig. 10 and Table 7 of the Authors' paper). Accordingly, their simultaneous use alongside SRP content (in Eqs. 1 and 2) introduces regressor

redundancy and the potential for multicollinearity (McClendon 2002; Daoud 2017; Soltani et al. 2022b). For instance, focusing on the redundancy issue, a simple regression analysis (performed by the Discussers) resulted in the following near-perfect S:ϕ and B:ϕ correlations (i.e., without the need of SRP content, and even without the UCS and c parameters, likely due to the limited number of data points involved in the modeling process):

$$S\ (\text{mm}) = -274.36 + 12.70 \times \phi\ \left(n = 6;\ R^2 = 0.986\right) \tag{3}$$

$$B\ (\text{kPa}) = -977.44 + 44.83 \times \phi\ \left(n = 6;\ R^2 = 0.996\right) \tag{4}$$

- Fig. 13 of the Authors' paper indicates that the six FEM simulations performed by the Authors pertain to an infinite strip footing resting on the compacted unamended and 1–5% SRP-amended soil investigated. This setup, which seemingly considers only a single width of strip footing, restricts the applicability of Eqs. 1 and 2 to the specific/limited conditions examined in the Authors' simulation study [i.e., in terms of soil type, SRP gradation and content, sample preparation (or compaction state), footing type and geometry, and for the undrained loading condition]. Hence, contrary to the Authors' narrative in which they stated that "… all the stakeholders can use the proposed regression equation to determine the bearing capacity and settlement of SRP-stabilized collapsible soil to stabilize the soil during construction projects …", Eqs. 1 and 2 (which were not validated using FEM or any other approach, as they were solely developed to predict the six FEM-generated data) cannot be applied more generally for different soil–SRP mixtures and/or dissimilar footing geometry/dimensions and loading scenarios.
- Unlike bearing capacity, the foundation settlement response is mainly governed by the soil stiffness attributes, rather than the soil strength properties (Budhu 2011). Accordingly, the sole reliance on strength attributes (i.e., the UCS, c and ϕ parameters obtained from quick-undrained testing) in Eq. 1 for predicting the settlement response of the compacted soil–SRP blends is debatable. In this context, it is the Discussers' viewpoint that the observed high correlation found between the settlement and strength-based parameters could likely arise from data-specific trends, and thus lacks a robust theoretical underpinning. That is, for performing settlement predictions, stiffness-related parameters should take precedence over strength properties, as they more accurately reflect the underlying physics of the problem. Consequently, contrary to the Authors' assertion that "… the settlement equation developed [i.e., Eq. 1] is a thorough model that takes into account several important variables affecting foundation settlement …", the functional expression given by Eq. 1 [i.e., $S = F(\text{UCS}, c, \phi)$] is highly unlikely to give reliable predictions beyond its specific/limited calibration domain, elaborated above. Finally, it is also worth noting that the predictions made by Eq. 1 correspond to the settlement occurring at the ultimate limit state (with no consideration of time-dependent behavior), which is often not a particularly useful prediction scenario for routine geotechnical engineering practice.

- The interpretations provided by the Authors regarding the intercept parameters in Eqs. 1 and 2 — in which the Authors claim that "… elastic deformation of the foundation and soil compression are two instances of the early effects on settlement that are captured by the intercept term [of Eq. 1] …" and "… initial settlement effects, such as soil compression and foundation deformation, are taken into account by the intercept [of Eq. 2] …" are fundamentally problematic. Given that the three strength-based regressors in Eqs. 1 and 2 always provide (both individual and collective) positive contributions to the predictions (i.e., ∀ SRP content: UCS, c and $\phi > 0$), the intercept terms cannot reflect any independent physical phenomenon. Instead, it is the Discussers' viewpoint that the intercept terms should be interpreted as 'offset' parameters, whose primary role is to mathematically adjust the combined interactions of the regressors for improved alignment of the predictions with the Authors' FEM-generated data. Given all the above (and considering the mathematical structure of Eqs. 1 and 2), the Authors' assertion that '*the intercept terms capture/reflect specific soil settlement effects'* misrepresents the actual role of the intercept terms in the modeling process.
- Another misinterpretation by the Authors concerns the regression coefficient (of −0.82) associated with the SRP content variable in Eq. 1. That is, the Authors' claim that "… the inverse link between the percentage of structural reinforcement and settlement is shown by SRP (%) (−0.82), suggesting that stronger reinforcement tends to reduce settlement since it increases soil stability …" lacks both theoretical and mathematical justification. As mentioned earlier, the UCS, c and ϕ parameters are themselves functions of the SRP content, such that attributing a direct physical interpretation to $-0.82 \times \text{SRP}$ in Eq. 1 without accounting for its strong interdependence with the other three (strength-based) regressors is fundamentally problematic. From a computational standpoint, the above argument coupled with the positive values of the UCS, c and ϕ parameters (across all SRP contents in the range of 1–5% investigated) ensures that the footing settlement cannot decrease solely because of increasing the SRP content.

Considering all the aforementioned points, it is the Discussers' viewpoint that a substantial increase in the sample (data) size relative to the number of regression coefficients—for instance, by the Authors generating additional FEM-based data for various soil types, SRP gradations and contents, soil–SRP compaction states, footing types and geometries, and applied loading conditions—is necessary to better assess the true potentials and/or limitations of the functional forms given by Eqs. 1 and 2, particularly in terms of input parameter suitability and model generalizability.

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Data Availability No datasets were generated or analyzed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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