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A Review of the Revised Soil Classification System (RSCS) Based on Plasticity and Electrical Sensitivity to Pore-Fluid Chemistry

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ABSTRACT
Environmental problems involving subsurface flow, sediment stability analyses, submarine excavation, engineered flow systems like groundwater pollutant movement and remediation, waste and barrier containment systems, hydrocarbon migration, resource recovery, and energy extraction applications are among the biggest challenges in recent times. Therefore, understanding the response of soil fabrics in these submerged conditions via soil classification becomes very crucial so as to ensure accurate assessment of the integrity and safety of underground constructions. However, limitations of the traditional Unified Soil Classification System (USCS) include the adoption of arbitrary criteria predicated on grain size distribution and the estimation of soil consistency limit using only deionized water, as such hinders the effective prediction of soil properties. This is in addition to having rigid fines plasticity boundaries and neglecting the crucial impact of pore-fluid chemistry (such as pH, ionic concentration, and permittivity) on the behaviour of fine-grained soil. On the other hand, the Revised Soil Classification System (RSCS) is physics-inspired and data-driven, simple, precise, and repeatable, though not without some fundamental constraints. The current study provides extensive and critical evaluation of the revised soil classification scheme based on plasticity and electrical sensitivity to pore-fluid chemistry. This was conducted by collating and synthesizing vast amount of primary research findings, and formulating a more coherent perspective, identifying potential knowledge gaps, and making recommendations for further studies. This study will inspire fine-tuning of the novel soil classification system and stimulate further research for widespread adoption in geotechnical, geophysical and other geo-related applications.

Keywords:
Fine-grained soils,
Plasticity,
Electrical Sensitivity,
Pore-Fluid Chemistry,
Revised Soil Classification.

INTRODUCTION

The geotechnical soil classification system is a meticulous means of compartmentalizing soils into different response groups corresponding to equivalent geotechnical properties, however, without a thorough description (Moreno-Maroto *et al.*, 2021; Prakash & Sridharan, 2021). In the traditional soil classification system, particle size is the first point of call, being simple and a property that cuts across all soils but with arbitrary scales for distinguishing soil fractions. In this scale, when soil grains are smaller than 75 µm or pass through sieve number 200, they are commonly referred to as fines or fine-grains. For clays, an upper particle size limit of 2 µm was recognized (Atterberg, 1905; BSI, 1957; Gilboy, 1930; Glossop & Skempton, 1945; Terzaghi, 1925) , and in some cases fixed at 5 µm while particles below 1 µm are referred to as colloids (AASHTO, 1950; ASCE, 1957; Goldbeck & Jackson, 1921). A fines content of 35 to 50 % indicates the shift in soil behaviour from coarse-grain to fine-grain dependent soil behaviour, while an upper plastic limit value of 50 distinguishes between high-plasticity and low-plasticity fines. The above description indicates the arbitrariness of the textural soil classification scheme. Despite the obvious arbitrariness, these grain sizes or textural scales have been applied in formulating various soil categorization systems, among which is the oldest versions of the Casagrande (1947) classification, called Unified Soil Classification System (USCS). As stated by Das (2004), geotechnical soil classification methods that rely on particle-size and consistency limits can be helpful when providing preliminary recommendations for other related applications, in classifying soils into comparable response groups, and in predicting potential geotechnical behavior. The traditional systems of soil classification is however a failure in a number of ways (Casagrande, 1947; Holtz & Kovacs, 1981; Kulhawy & Chen, 2009); in the sense that particle size distribution cannot make comprehensive prediction of the properties of soils because equal distributions of particle sizes within soils can result in a variety of physical properties. Also, the system adopted rigid fines plasticity boundaries, disregarded fines thresholds for various properties, and ignored the pivotal influence of pore-fluid chemistry (such as pH, ionic concentration, and permittivity) on fine-grained soil behaviour (Jang & Santamarina, 2017b). The traditional (USCS) method of classifying fine-grained soil using deionized water as the only pore-fluid is inadequate in effectively providing thorough geotechnical assessment of soils and subsequent prediction of their behavior, especially in the case of fine-grains and substantial fines proportion of coarse-grains where the predominant component is plasticity. Resolving these limitations are very necessary in the light of chemical transformations related to subsurface flow, sediment stability analyses, submarine excavation, engineered flow systems like groundwater pollutant movement and remediation, waste and barrier containment systems, hydrocarbon migration, resource recovery, and energy extraction applications.

On the other hand, the revised soil classification system (RSCS) distinguishes fine-grained soils according to plasticity and electrical sensitivity to the pore-fluid chemistry. Plasticity is the tendency of clays or clayey materials to be molded to any form without rupture or crack (Guggenheim & Martin, 1995). The above definition of plasticity depicts the idea of 'toughness', which emphasizes the degree of work necessary to deform a given soil sample; so more toughness and plasticity of the soil, entails greater effort required (Barnes, 2009, 2013a, 2013b; Casagrande, 1947). Whereas, the electrical sensitivity is a measure of fine sediment's response to changes in permittivity and electrical conductivity of pore-fluid (Jang & Santamarina, 2016). It is a measure of the degree to which variation in pore-fluid chemistry alters microscopic interparticle interactions in soils, which culminates into alterations in macroscopic soil properties (Jang *et al.*, 2018). Particle-fluid interaction determines the variations in the thickness of diffuse double layer surrounding the grain surface. The double layer thickness is dependent on temperature, ionic strength, dielectric permittivity, ion concentration, and valence, while specific surface area, particle morphology, mineralogy, and grain sizes affects how the double layer alters the response of fine-grained soil. The revised soil classification system is very relevant in multiple areas such as controlled pore-fluid replacement applications, like the mining of methane from gas hydrate, oil and gas mining (Mohan *et al.*, 1993; Oyama *et al.*, 2016), geological carbon dioxide (CO_2) sequestration (Pudlo *et al.*, 2015), near-surface fluid contaminants processes (Mackay & Cherry, 1989), reconditioning of liquids in non-aqueous phases (Glass *et al.*, 2000; Rao *et al.*, 1997). Chemical changes in pore-fluids alters index properties of fine-grained soil and other particle-fluid interaction phenomenon (Mitchell & Soga, 2005b; Santamarina *et al.*, 2002b) such as sediment compressibility, degree of instability, and fluid permeability dynamics (Andersson-Skold *et al.*, 2005; Austad *et al.*, 2008; Frederick & Buffett, 2015; Kopf *et al.*, 2010; Sultan *et al.*, 2004).

Regarding the test protocol, among the numerous tests for index properties that were conducted to decide the best criteria for the revised fine-grained soil classification system in terms of plasticity and electrical sensitivity, consistency limit was the most preferred (Jang, 2014), because it provides accurate, fast, reliable and repeatable results, it is not affected by boundary effects and enjoys a wealth of published laboratory and field experience. This novel test protocol has proven to be so effective that recent studies have succeeded in using it to evaluate a number of geotechnical parameters namely hydraulic conductivity, shear resistance, over-consolidation ratio, soil suitability analysis and soil compressibility using correlations with consistency limit (Dolinar, 2009; Ike *et al.*, 2023; Jang, 2022; Jang *et al.*, 2018; Lee *et al.*, 2005; Prahara *et al.*, 2021; Sridharan & Nagaraj, 2005; Won *et al.*, 2021). This study aims to comprehensively conduct a state of the art critique on the revised soil classification system for fines-grains. To carry out this review, we blended the research outputs from multiple primary sources to create a unified viewpoint, offered targeted discussion of this innovative classification scheme, delineated possible knowledge gaps, and proffered credible suggestions for further research.

MATERIALS AND METHODS

Materials

Sampled Soils

The widely collated database (Table 1) contains details of mono-mineral and poly-mineral natural soils, organic, intra-porous soils. The samples include Bentonite, Natural soils, Mexico City soil, Diatom/Diatomite, Volcanic ash, Red Sea Sediment, Fly ash, LKW Kaolinite, AMK Kaolinite, EPK Kaolinite, YI Illite, MI Illite, Ottawa 20-30 sand, Silica flour, Kaolinite, Illite, Red sea sed (Microfossils), Piedmont GA-1, Piedmont GA-2, Clay Adairville GA-1, Clay Adairville GA-2, Silt Matanuska Glacier, Ponza bentonite, Bisaccia clay, Organic powder – starch, Organic powder (intraporous), Silica silt, Mica, Calcium Carbonate Powder $CaCo_3$, Green Clay, Mesilla Soil, Kaolin mixtures (40:60, 60:40 respectively), Portland soil, Kaolinite: Silica flour mixtures (0:100, 25:75, 50:50, 75:25 and 100:0 respectively), Bentonite: kaolinite mixtures (100:0, 75:25, 50:50, 25:75 respectively), Sand, Zeolite, Silt, Weathered mudstone (Silurian), Coode Island silt, Wollert basaltic clay, Mount Ridley basaltic clay, Braybrook basaltic clay, Land cover: Queensland, Silty clay (Melbourne Silurian), Offshore Santa Barbara Channels (1, 2, 34,), Galveston (Texas) soil, Redart clay, Volcanic ash, Tsai silty clay, Oregon red clay, Barcellona soil, Raw kaolin (clayey silt), Dresden (Germany) soil, Y02, Y01, X25, X24, S20, S31, S41, S50, DS11, B3, S7, DS1, X33, DS1, G01, X20, X19, X18, G06, S9, S10, G05, G04, G03 and Silica silt (Bandini *et al.*, 2017; Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang *et al.*, 2018; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Martinez *et al.*, 2017; Montoro & Francisca, 2017; Narsilio *et al.*, 2017; Prahara *et al.*, 2021; Schneider *et al.*, 2017).

Pore-Fluids Used

The pore-fluids used are electrically contrasting, namely kerosene, 2 M NaCl solution (brine) and deionized water (represented by the subscripts 'ker', 'brine', and 'DW' respectively) prepared with pure salt and deionized water. Each pore-fluid was intentionally selected; the deionized water amplifies double-layer effects and inhibits the emergence of face-to-face aggregation, the non-polar or low polarity kerosene was chosen to examine the impact of Van der Waals forces inter-particle attraction by eliminating hydration and osmotic effect, whereas, the 2 M NaCl solution breaks down the double layer and to annihilate possible ambivalence caused by inherent or residual ions in the soil (Ike et al., 2023; Santamarina et al., 2019). Also, the liquid limit ratios were adjusted for effects due to variations in the unit weights of kerosene and deionized water, as well as the formation of salt residue during oven drying in the case of NaCl solution as pore-fluid (Narsilio et al., 2017).

Methods

Estimation of Liquid Limit and Plastic Limit

The inherent subjectivity experienced in the "Casagrande cup" method in liquid limit estimation and 3.2 mm diameter thread-rolling method in estimating plastic limit were eliminated through the use of the fall cone penetrometer. The fall cone penetrometer used in determining the liquid was of 80 g cone with 30-degree apex angle (ASTM D4318, 2005; BS 1377, 1990) while that for plastic limit was 240 g cone with 30-degree apex angle (Wood & Wroth, 1978). The cone penetrations for each soil paste corresponding to each pore-fluid (deionized water, 2 M NaCl solution and kerosene) were carried out following standard test procedures (ASTM, 2010; ASTM D4318, 2005; BS 1377, 1990).

Conceptual Framework

The new classification protocol for fines blended the liquid limit values derived from the three (3) electrically contrasting pore-fluids into two liquid limit quotients as, LL_{DW}/LL_{brine} and LL_{ker}/LL_{brine}, where LL_{DW}, LL_{brine}, and LL_{ker} are designations for liquid limit values for deionized water (DW), 2 M NaCl solution (brine) and kerosene (ker) respectively.

Plasticity of the Soil Samples due to Pore-Fluid Chemistry S_E

The liquid limit ratio LL_{ker}/LL_{brine} is indicative of the changes in fine-grained soil behavior as a result of alterations in pore-fluid permittivity, while LL_{DW}/LL_{brine} addresses the decrease in double-layer thickness attributable to the spike in conductivity of the permeant fluid, since LL_{DW} is typically greater than LL_{brine} (Santamarina *et al.*, 2002a). The respective equations are (Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang & Santamarina, 2016);

$$LL_{brine} = LL_{brine}\frac{1}{1-C_{brine}\frac{LL_{brine}}{100}} \quad (1)$$

$$\left.\frac{LL_{DW}}{LL_{brine}}\right] = \frac{LL_{DW}}{LL_{brine}}\left(1 - C_{brine}\frac{LL_{brine}}{100}\right) \quad (2)$$

And

$$\left.\frac{LL_{ker}}{LL_{brine}}\right] = \frac{LL_{ker}}{LL_{brine}}\frac{1-C_{brine}\frac{LL_{brine}}{100}}{G_{ker}} \quad (3)$$

where C_{brine} in the above equations is the NaCl concentration in weight while G_{ker} is the manufacturer defined specific gravity of kerosene (0.78) (Jang & Santamarina, 2017a).

Electrical Sensitivity of the Soil Samples to Pore-Fluid Chemistry S_E

Equations 4 and 5 were used in computing the electrical sensitivity to pore-fluid chemistry S_E, which is technically the difference between a measured data point and the absolute "non-sensitive" soil response point on the graph (1,1) at $LL_{ker}/LL_{brine} = 1.0$ and $LL_{DW}/LL_{brine} = 1.0$. Therefore (Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang & Santamarina, 2016; Jang. & Santamarina., 2017);

Left: $\frac{LL_{ker}}{LL_{brine}} > 1$

$$S_{E(left)} = \sqrt{\left(\frac{LL_{ker}}{LL_{brine}} - 1\right)^2 + \left(\frac{LL_{DW}}{LL_{brine}} - 1\right)^2} \quad (4)$$

Right: $\frac{LL_{DW}}{LL_{brine}} > 1$

$$S_{E(right)} = \sqrt{\left(\frac{LL_{brine}}{LL_{ker}} - 1\right)^2 + \left(\frac{LL_{DW}}{LL_{brine}} - 1\right)^2} \quad (5)$$

left and *right* in in equations 4 and 5 respectively refer to the two flanks of the abscissa in relation to a defined non-sensitive soil response point (1,1). Also, the inverse values of the ratios are plotted on the reverse quadrant to provide an equivalent estimate of the electrical sensitivity to pore-fluid chemistry at instances where either liquid limit ratio is less than unity.

Classification Protocol for the Fine-grained Soil

Boundaries for the revised fine-grained soil classification across the collated samples are (Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang & Santamarina, 2016):

boundaries for the Plasticity of the Samples due to Pore-Fluid Chemistry S_E;

$LL_{brine} \leq 30$ for very loose sands and none plastic fines,
$LL_{brine} = 30 – 50$ for low plasticity fines,
$LL_{brine} = 50 – 75$ for Intermediate plasticity fines (kaolinite and illite) and
$LL_{brine} > 75$ for High plasticity fines (smectite).

boundaries for the Electrical Sensitivity of the Soil Samples to Pore-Fluid Chemistry S_E;

$S_E < 0.40$ for None/low electrical sensitivity
$S_E = 0.40 – 1.0$ for Intermediate electrical sensitivity (kaolinites and illite) and
$S_E > 1.0$ for high electrical sensitivity (smectite)

Table 1: Summary of Literature Review on the Revised Fine-grained Soil Classification System (RSCS)
H = High; I = Intermediate; L = Low; N = Non-

AUTHOR	SOIL DESCRIPTION	MEAN PARTICLE SIZE D_{50} (µm)	SPECIFIC SURFACE AREA (m^2/g)	PLASTIC LIMIT (%)	PASS NO 200 SIEVE (%)	LIQUID LIMIT (%)			USCS	PROPOSED CLASSIFICATION GROUP	
						DEIONIZED WATER	BRINE	KEROSENE		PLASTICITY	ELECTRICAL SENSITIVITY (S_E)
ORIGINAL PAPER Jang and Santamarina (2016)	Ottawa 20-30 Sand	720	0.003	20	~ 0	22	19	20	SP	N	L
	Silica Flour	20	0.5	26	100	31	26	28	ML	N	L
	Diatom	10	89	113	100	121	110	138	MH	H	L
	Fly ash	20	2.1	47	95	50	47	45	ML	L	L
	Kaolinite	0.36	34	31	100	67	52	82	CH	I	I
	Illite	0.5	110	29	100	67	62	37	CH	I	I
	Bentonite	0.07	565	44	100	276	92	39	CH	H	H
	Red Sea Sediment (Microfossils)	120	48	110	36	263	100	55	SW	H	H
	Piedmont GA-1	-	-	34	100	53	44	50	CH	L	L
	Clay Adairville GA-1	-	-	37	97	65	45	52	CH	L	I
	Silt Matanuska Glacier	-	-	25	100	33	32	40	ML	L	I
	Piedmont GA-2	-	-	40	100	63	57	67	CH	I	L
	Clay Adairville GA-2	-	--	34	97	91	53	68	CH	I	I
	Ponza Bentonite	-	-	70	88	390	90	65	CH	H	H
	Bisaccia Clay	-	-	60	83	110	65	30	MH	I	H
	Organic Powder-starch	-	-	37	100	75	66	57	OH	I	L
	*Organic Powder (intra porous)	-	-	120	100	127	107	47	OH	H	H
	Calcium Carbonate Powder ($CaCO_3$)	-	-	17	-	25	23	31	CL	N	I
	Kaolinite	-	24	38	-	81	55	83	MH	I	I
	Green Clay: Illite	-	18	28	-	50	48	57	CH	L	I
	Bentonite	-	579	54	-	288	126	65	CH	H	H
	Fly Ash: TCP-1	-	-	-	-	50	47	48	-	L	L
	Fly Ash: TCP-2	-	-	-	-	45	36	36	-	L	L
	Fly Ash: TVA	-	-	-	-	36	30	31	-	L	L

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						DEIONIZED WATER	BRINE	KEROSENE		PLASTICITY	ELECTRICAL SENSITIVITY (S_E)
Bandini and Al Shatnawi's discussion (2017)	Mesilla Soil	60	48	21	-	41	40	41	CL-ML	L	L
	Kaolin	0.7	26	31	-	54	46	66	ML	L	I
	Diatomite	3.5	112	94	-	123	101	124	MH	H	L
	Diatomite: Kaolin (40:60)	1.1	60	47	-	72	63	86	MH	I	I
	Diatomite: Kaolin (60:40)	1.8	73	61	-	87	74	97	MH	I	I
Khoubani and Evans's discussion (2017)	Portland	-	-	-	-	43	40	35	CL	L	L
	Kaolinite	-	-	-	-	53	56	91	CH	I	I
	Bentonite	-	-	-	-	552	148	54	CH	H	H
Martinez et al.'s discussion (2017)	Kaolinite: Silica flour (0:100)	-	-	-	-	65	55	65	-	I	L
	Kaolinite: Silica flour (25:75)	-	-	-	-	51	40	51	-	L	L
	Kaolinite: Silica flour (50:50)	-	-	-	-	39	31	42	-	L	L
	Kaolinite: Silica flour (75:25)	-	-	-	-	33	27	35	-	N	I
	Kaolinite: Silica flour (100:0)	-	-	-	-	29	27	26	-	N	L
	Bentonite: kaolinite (100:0)	-	-	-	-	509	103	58	-	H	H
	Bentonite: kaolinite (75:25)	-	-	-	-	341	105	55	-	H	H
	Bentonite: kaolinite (50:50)	-	-	-	-	220	71	57	-	I	H
	Bentonite: kaolinite (25:75)	-	-	-	-	132	66	58	-	I	I
Montoro and Fracisca's discussion (2017)	Sand	1000	-	-	-	7	6.5	6	-	N	L
	Bentonite	-	731	192	-	309	113	44	MH	H	H
	Kaolinite	-	58	36	-	43	40	47	ML	L	L
	Zeolite	11	61	42.1	-	50	48	36	MH	L	L
	Silt	5	1.1	22.5	-	25	21	24	MH	N	I
	Weathered mudstone (Silurian)	20	25	21	-	32	25	41	CL	N	H

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						DEIONIZED WATER	BRINE	KEROSENE		PLASTICITY	ELECTRICAL SENSITIVITY (S_E)
Narsilio et al.'s discussion (2017)	Coode Island silt	10	61	23	-	67	41	35	CH	L	I
	Wollert basaltic clay	1	232	27	-	61	53	32	CH	I	I
	Mount Ridley basaltic clay	1	257	40	-	69	54	33	MH	I	I
	Braybrook basaltic clay	5	210	30	-	67	50	30	CH	I	I
	Arumpo bentonite	1	526	44	-	167	78	54	CH	H	I
	Land cover: Queensland	2	24	15	-	21	21	32	CL-ML	N	I
	Silty clay (Melbourne Silurian)	2	80	20	--	48	40	47	CL	L	I
Schneider et al.'s discussion (2017)	Silica flour	13	1.5	26	-	31	30	31	ML	L	L
	Diatomaceous earth	3.7	103	99	-	130	111	138	MH	H	L
	LPC kaolin	2.4	26	26	-	53	48	74	CH	I	I
	Edgar plastic kaolin (EPK)	0.34	44	32	-	69	59	60	CH	I	L
	Montmorillonite			48	-	450	80	38	CH	H	H
	Santa Barbara Channel 1 (offshore)	13	35	28	-	45	41	42	ML	L	L
	Santa Barbara Channel 2 (offshore)	14	34	31	-	39	37	37	ML	L	L
	Santa Barbara Channel 3 (offshore)	13	26	29	-	37	35	37	ML	L	L
	Santa Barbara Channel 4 (offshore)	11	35	29	-	51	48	56	ML	I	L
	High-plasticity clay, Galveston, Texas	0.42	132	33	-	96	63	36	CH	I	I
	Redart clay	6.9	36	21	-	40	40	43	CL	L	L
*Arduino et al., University of Washington (2017)	Volcanic ash	-	-	-	-	380	83	47	-	H	H
	Kaolin	-	-	-	-	62	66	88	-	I	L
	Tsai silty clay	-	-	-	-	39	35	43	-	L	L
	Oregon red clay	-	-	-	-	40	45	52	-	L	L

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						DEIONIZED WATER	BRINE	KEROSENE		PLASTICITY	ELECTRICAL SENSITIVITY (S_E)
*Cordero J., UPC (2017)	Barcelona soil	-	44	19	-	34	36	32	-	L	L
*Herle et al. Technishe Universität Dresden (2017)	Raw kaolin (clayey silt), Dresden, Germany	-	-	32	-	47	43	54	ML	L	I
	Silica Silt								ML		
	Mica	10.5	0.2	30	-	31	31	36	-	L	I
	Calcium	17	4.2	80	-	94	81	110		H	I
Jang et al.,	Carbonate	8	0.2	17	-	25	23	31	-	N	I
(2018)	Powder ($CaCO_3$)	10	98	98	-	119	111	140	MH	H	I
	Diatoms	4	24	38	-	77	55	83	CH	I	I
	Kaoline	20	29	32	-	56	52	59	CH	I	L
	Illite	< 2	579	54	-	288	126	65		H	H
	Bentonite								CH		
	Y02	-	-	43.75	-	-	62.76	-	MH	I	I
	Y01	-	-	34.13	-	-	47.56	-	MH	L	I
	X25	-	-	49.96	-	-	53.55	-	MH	I	1
	X24	-	-	65.66	-	-	40.19	-	MH	L	I
	S2 0	-	-	33.87	-	-	101.17	-	MH	H	I
	S3	-	-	34.54	-	-	46.64	-	MH	L	L
	S4	-	-	39.16	-	-	68.66	-	MH	I	I
	S5	-	-	30.16	-	-	48.68	-	MH	L	L
Prakash, K.,	DS11	-	-	40.75	-	-	43.11	-	MH	L	L
Sridharan,	B03	-	-	45.72	-	-	48.62	-	MH	L	L
A., (2021)	S7	-	-	33.26	-	-	46.57	-	MH	L	L
	DS13	-	-	43.19	-	-	44.81	-	MH	L	I
	X33	-	-	53.94	-	-	56.91	-	MH	I	I
	DS1	-	-	86	-	-	52.55	-	MH	I	H
	G01	-	-	39.65	-	-	39.55	-	MH	L	I
	X20	-	-	46.98	-	-	32.12	-	MH	L	I
	X19	-	-	65.45	-	-	42.51	-	MH	L	H
	X18	-	-	50.87	-	-	38.98	-	MH	L	H
	G06	-	-	33.19	-	-	36.94	-	MH	L	L
	S9	-	-	30.25	-	-	54.61	-	MH	I	1
	S10	-	-	34.05	-	-	51.93	-	MH	I	L

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						DEIONIZED WATER	BRINE	KEROSENE		PLASTICITY	ELECTRICAL SENSITIVITY (S_E)
	G05	-	-	49.14	-	-	59.17	-	MH	I	I
	G04	-	-	36.41	-	-	48.78	-	MH	L	I
	G03	-		43.75	-	-	47.26	-	MH	L	H
Ike et al., (2023)	Kaolinite (LWK)	23.0	9.79	21.50	200	43.78	37.375	44.039	-	L	I
	Kaolinite (AMK)	0.6	68.50	51.0	200	82.31	53.509	61.636	-	I	I
	Kaolinite (EPK)	1.4	59.40	43.90	200	400	51.636	75.583	-	I	I
	Illite (MI)	20	10.70	25.30	200	49.28	150	45.1	-	L	L

RESULTS AND DISCUSSION
Results

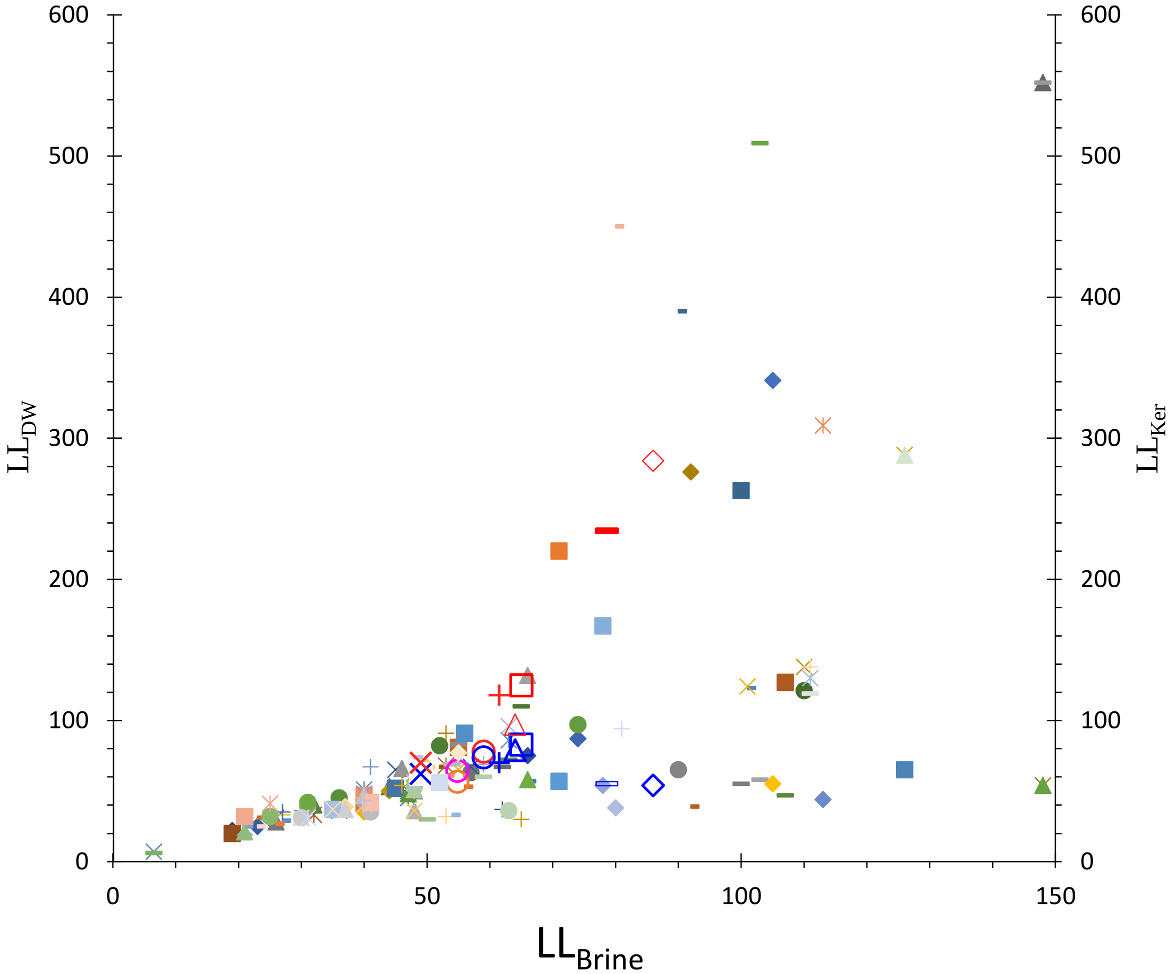

Figure 1: Database of the variation of liquid limit values of soils permeated with deionized water (LL_{DW}), 2 M NaCl solution (LL_{brine}) and kerosene (LL_{ker}). The database contains notable mono-mineral and poly-mineral natural soils, organic materials, and intra-porous soils (Arduino et al.; Bandini et al., 2017; Cordero J.; Herle et al.; Ike et al., 2023; Jang & Santamarina, 2017a; Jang et al., 2018; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Martinez et al., 2017; Montoro & Francisca, 2017; Narsilio et al., 2017; Schneider et al., 2017).

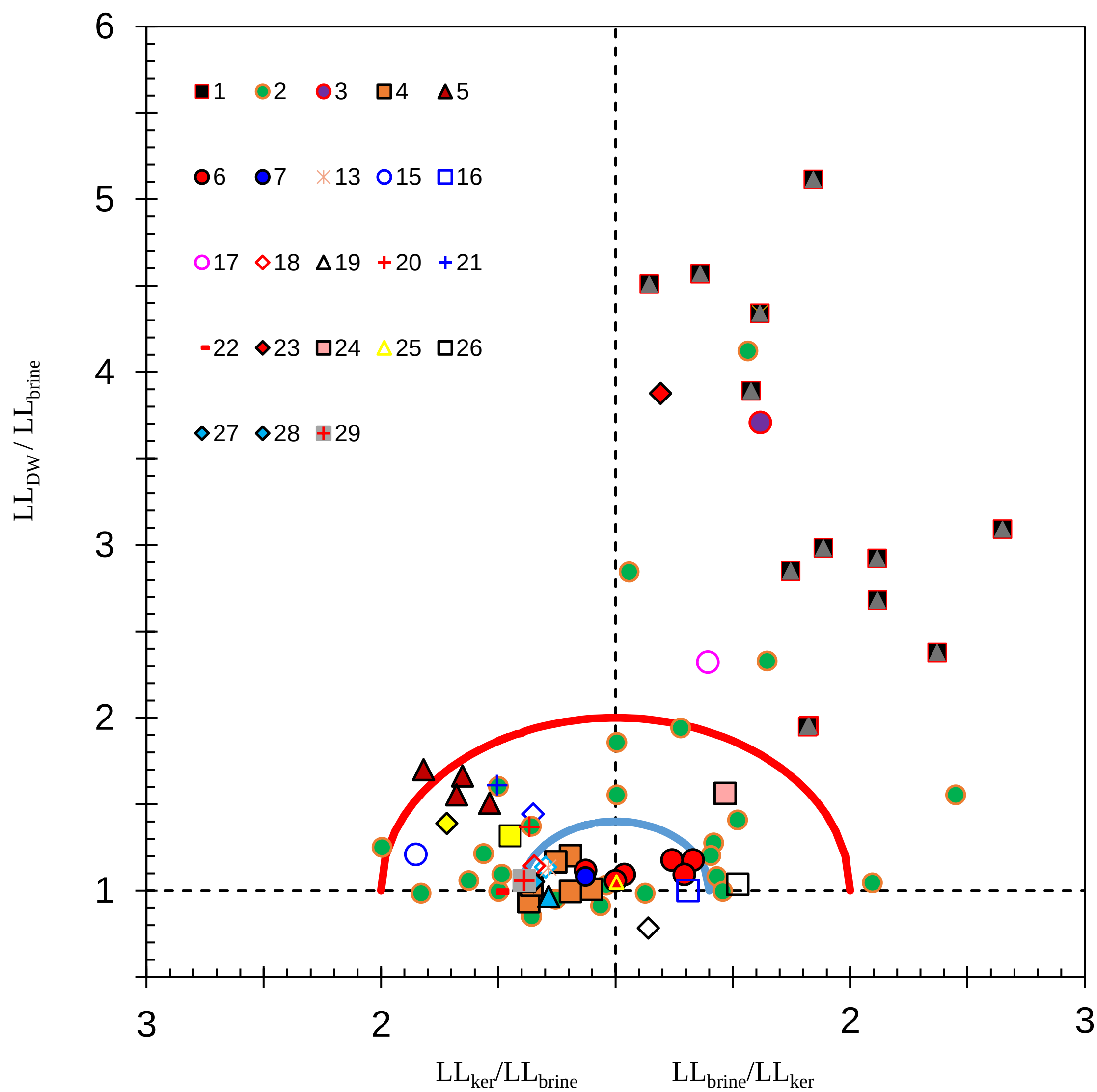

Figure 2: Liquid limit ratios and electrical sensitivity to pore-fluid chemistry. The figure shows fines response to variations in conductivity and permittivity. The insets define electrical sensitivities S_E = 1.0 (red line) and S_E = 0.4 (blue line). The database contains notable mono-mineral and poly-mineral natural soils, organic materials and intra-porous soils (Arduino et al.; Bandini *et al.*, 2017; Cordero J.; Herle et al.; Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang *et al.*, 2018; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Martinez *et al.*, 2017; Montoro & Francisca, 2017; Narsilio *et al.*, 2017; Schneider *et al.*, 2017). Legend: 1. Bentonite 2. Natural soils, 3. Mexico City soil, 4. Diatom/Diatomite, 5. Volcanic ash, 6. Red Sea Sediment, 7. Fly ash, 8. LKW Kaolinite, 9. AMK Kaolinite, 10. EPK Kaolinite, 11. YI Illite, 12. MI Illite, 13. Ottawa 20-30 sand, 14. Silica flour, 15. Kaolinite, 16. Illite, 17. Red sea sed (Microfossils), 18. Piedmont GA-1, 19. Piedmont GA-2, 20. Clay Adairville GA-1, 21. Clay Adairville GA-2, 22. Silt Matanuska Glacier, 23. Ponza bentonite, 24. Bisaccia clay, 25. Organic powder – starch, 26. Organic powder – intraporous, 27. Silica silt, 28. Mica, 29. Calcium Carbonate Powder ($CaCo_3$).

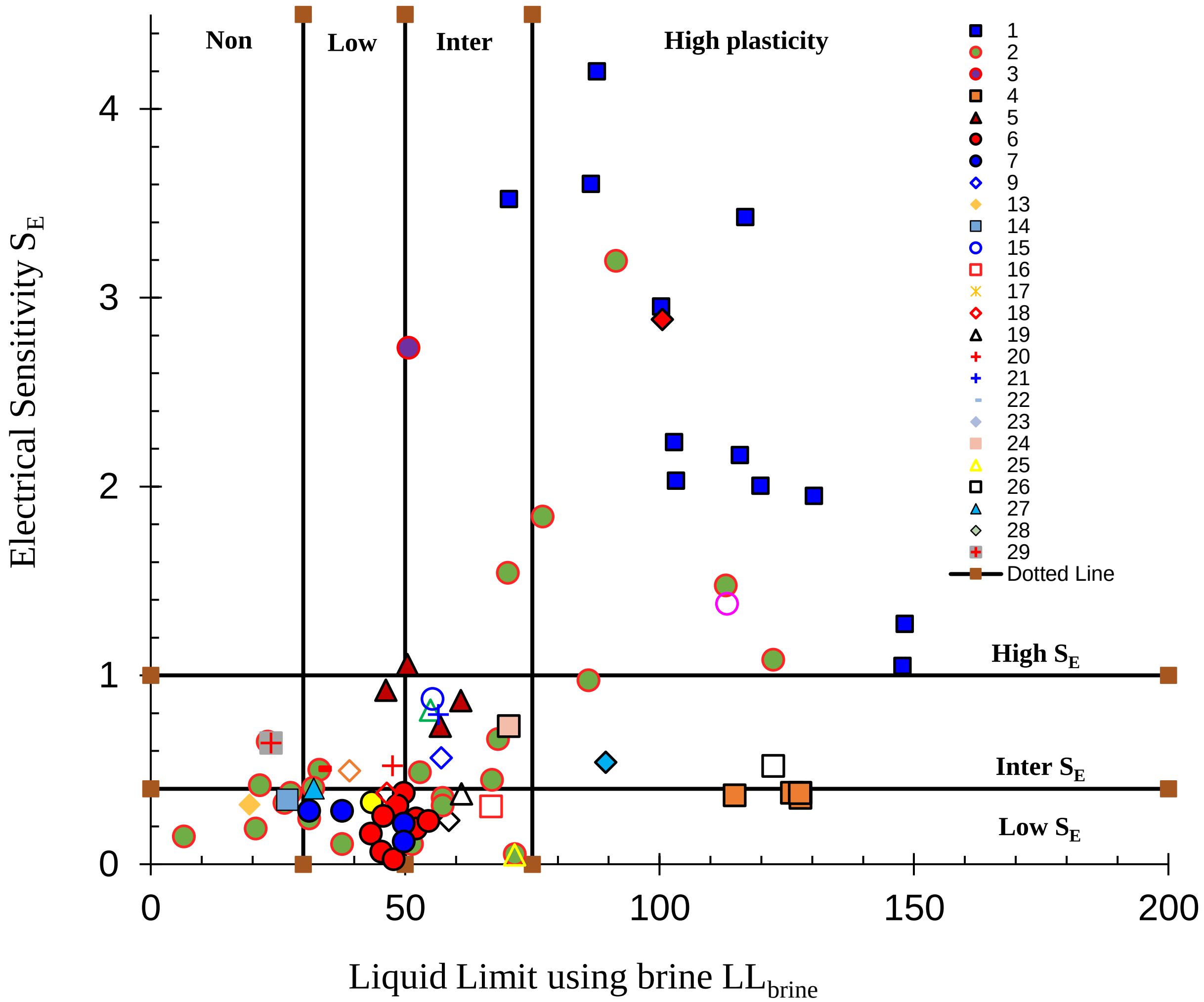

Figure 3: The revised soil classification chart for fines, containing the 12 response groups (refer Equation 4 and 5). The database contains notable mono-mineral and poly-mineral natural soils, organic materials, and intra-porous soils (Arduino et al.; Bandini *et al.*, 2017; Cordero J.; Herle et al.; Ike *et al.*, 2023; Jang & Santamarina, 2017a; Jang *et al.*, 2018; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Martinez *et al.*, 2017; Montoro & Francisca, 2017; Narsilio *et al.*, 2017; Schneider *et al.*, 2017). Legend: 1. Bentonite 2. Natural soils, 3. Mexico City soil, 4. Diatom/Diatomite, 5. Volcanic ash, 6. Red Sea Sediment, 7. Fly ash, 8. LKW Kaolinite, 9. AMK Kaolinite, 10. EPK Kaolinite, 11. YI Illite, 12. MI Illite, 13. Ottawa 20-30 sand, 14. Silica flour, 15. Kaolinite, 16. Illite, 17. Red sea sed (Microfossils), 18. Piedmont GA-1, 19. Piedmont GA-2, 20. Clay Adairville GA-1, 21. Clay Adairville GA-2, 22. Silt Matanuska Glacier, 23. Ponza bentonite, 24. Bisaccia clay, 25. Organic powder – starch, 26. Organic powder – intraporous, 27. Silica silt, 28. Mica, 29. $CaCo_3$

Discussion

Liquid limit values of soils permeated with the three pore-fluids

Figure 1 shows the disparities in liquid limit values and ratios of soils permeated with deionized water (LL_{DW}), 2 M NaCl solution (LL_{brine}) and kerosene (LL_{ker}). Despite the difference in compositions and index properties of the samples (Figure 1.), liquid limit with deionized water (LL_{DW}) was higher than that of NaCl solution (LL_{brine}), suggesting the interaction between grain surface and very negligible ionic concentration of the deionized water, whereby the fluid retention capacity and interparticle repulsion is enhanced leading to expansion in the thickness of double layer, and the resultant higher porosity fabric. A high LL_{DW}/LL_{brine} ratios is indicative of fines that are sensitive to variations in pore-fluid ionic concentration. Example of such situation is shrinkage during salt-water (brine) intrusion in soil and in rain-induced dispersion. On the contrary, fine-grains with high LL_{ker}/LL_{brine} ratio, reveals sensitivity to variations in pore-fluid polarity. Such is the case in the incursion of non-aqueous phase liquids (NAPLs) or Carbon-dioxide (CO_2) injection for storage purposes in geology and geophysics (Won *et al.*, 2021). Therefore, the phenomenon of electrical sensitivity index is a means of pre-empting possible changes in fabric when fine-grained soils are subjected to changes in pore-fluid chemistry.

However, some samples such as Bentonites, binary mixtures of Bentonites and kaolinite (Ike *et al.*, 2023; Jang *et al.*, 2018; Jang & Santamarina, 2016; Martinez *et al.*, 2017; Montoro & Francisca, 2017; Narsilio *et al.*, 2017; Schneider *et al.*, 2017), Portland soil (Khoubani & Evans, 2017), zeolite (Montoro & Francisca, 2017), Volcanic ash (Arduino et al.), Galveston (Texas) clay (Schneider *et al.*, 2017), Red Sea Sediment (Microfossils), Bisaccia Clay, Organic Powder-starch, intra-porous organic Powder (Jang & Santamarina, 2016) and Coode Island silt, Wollert basaltic clay, Mount Ridley basaltic clay, Braybrook basaltic clay (Narsilio *et al.*, 2017) showed liquid limit values with brine (LL_{brine}) higher than that of kerosene (LL_{ker}) (Table 1). This is probably because of the presence of localized surface charge, high specific surface areas, and whose influence are much more obvious in low permittivity fluid (kerosene) than in ionic solutions, thereby giving rise to fabric clustering and an increase in porosity. Moreover, the high ionic concentrations of the brine must have caused the double layer thickness to wane, thereby strengthening the likelihood of hydration which increases LL_{brine} above LL_{ker} (Ike et al.,, 2023). Concerning the binary mixtures of bentonite (B) and kaolinite (K), increasing the proportion of bentonite leads to a rise in the estimated liquid limit and plasticity value of the mixture (Polidori, 2009; Schmitz *et al.*, 2004b), except in the case of kerosene which appears generally independent of the bentonite fraction (Martinez *et al.*, 2017). This in all likelihood is because the composition of kaolinite and bentonite underwent diverse forms of interaction with the low permittivity fluid (kerosene), in the sense that for kerosene, liquid limit increases because of edge charges and Vander Waals forces (Santamarina *et al.*, 2002b), whereas for bentonite, liquid limit declines as a consequence of the diminution in the thickness of the double layer (Mitchell & Soga, 2005a).

Also, across all samples with low specific surface areas and low plasticity, liquid limit with kerosene (LL_{ker}) was greater than liquid limit with brine (LL_{brine}). This trend was observed for kaolinite (Ike *et al.*, 2023; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Montoro & Francisca, 2017); illite (Ike *et al.*, 2023; Jang *et al.*, 2018; Jang & Santamarina, 2016); Silt (Montoro & Francisca, 2017); Piedmont GA-1, Clay Adairville GA-1, Silt Matanuska Glacier, Piedmont GA-2, Clay Adairville GA-2, fly ash and Calcium Carbonate Powder (Jang & Santamarina, 2016); Mesilla Soil, Kaolin, Diatomite, Diatomite-Kaolin mixtures (40:60 and 60:40) (Bandini *et al.*, 2017); binary mixtures of Kaolinite (K)-Silica flour (S) (0:100; 25:75; 50:50; 75:25) (Martinez *et al.*, 2017); Queensland land cover, Melbourne Silurian silty clay, Silurian weathered mudstone (Narsilio *et al.*, 2017); Silica flour, LPC kaolin, Edgar plastic kaolin, offshore Santa Barbara Channels (1, 3 and 4), Redart clay (Schneider *et al.*, 2017) and Silica Silt, Mica, $CaCo_3$, Kaoline (Jang *et al.*, 2018). This behaviour is probably because kerosene has the tendency to penetrate and occupy the intergrain pores much easily than brine and water, hence $\frac{LL_{ker}}{LL_{brine}}$ becomes greater than unity.

Lastly, the liquid limit of diatomite and diatomite: kaolinite mixtures are high, and increase even more with increase in diatomite content. This is probably because of the intraparticle porosity and strong ability to hold fluid within the intergrain voids of the diatomite and not necessarily because of the plasticity value (Bandini *et al.*, 2017; Ike *et al.*, 2023). This therefore indicates that since the addition of diatomite increases the plasticity of sample mixtures, though with a reduction in electrical sensitivity, in classifying natural soils containing at least 20% by weight of diatom microfossils using the revised soils classification system (RSCS), there is a need to be very mindful of the prepondering influence of the diatoms and their likes (Bandini *et al.*, 2017). Also, soil samples can unexpectedly show slightly different behaviour on the RSCS chart (Jang & Santamarina, 2016) as was observed in some kaolin and diatomite sample (Bandini *et al.*, 2017). This is attributable to the intrinsic variability, difference in grain morphology, mineralogy, sample gradation and production procedures.

Plasticity and electrical sensitivity of the soils to pore-fluid chemistry

Figure 2 shows fines response to variations in conductivity and permittivity of the pore-fluids, while Figure 3 shows the revised classification for fines based on electrical sensitivity to pore-fluids S_E. The database indicates that soils with high specific surface areas, namely smectite group (bentonite/montmorillonite), bentonite dominated binary mixtures, volcanic ash, natural soils, red sea sediment (microfossils), and *organic powder (intra-porous) classifies as high plasticity and high electrical sensitivity to pore-fluid chemistry as observed in Ike *et al.* (2023); Jang *et al.* (2018); Jang and Santamarina (2016); Khoubani and Evans (2017); Martinez *et al.* (2017); Montoro and Francisca (2017); Narsilio *et al.* (2017); Schneider *et al.* (2017). Whereas samples with low (mean) particle size

D_{50} (μm) and comparatively lower plastic limit comprising of kaolinite, kaolin and illite clay samples were categorized as intermediate plasticity and intermediate electrical sensitivity to pore-fluid chemistry soils (Ike *et al.*, 2023; Jang *et al.*, 2018; Jang & Santamarina, 2016; Khoubani & Evans, 2017; Schneider *et al.*, 2017). This also applies to Wollert basaltic clay, Mount Ridley basaltic clay, Braybrook basaltic clay from Melbourne metropolitan area (Narsilio *et al.*, 2017), diatom-kaolin mixtures (40;60, 60;40) (Bandini *et al.*, 2017), bentonite-kaolinite mixtures (25;75) (Martinez *et al.*, 2017) and Galveston Texas clay (Schneider *et al.*, 2017). Also, the low plasticity and low electrical sensitivity soils comprising mostly fly ash, Piedmont GA-1 soils (Jang & Santamarina, 2016), mesilla soil (Bandini *et al.*, 2017), Portland soil (Khoubani & Evans, 2017), kaolinite-silica floor mixtures (25:75. 50:50) (Martinez *et al.*, 2017), zeolite (Montoro & Francisca, 2017), silica floor, redart clay, Offshore Santa Barbara Channels 1, 2, and 3 (Schneider *et al.*, 2017), Tsai silty clay, Oregon red clay (Arduino et al.) and MI illite (Ike *et al.*, 2023). However, Sand (Jang & Santamarina, 2016; Montoro & Francisca, 2017), Silica Flour (Jang & Santamarina, 2016) and Kaolinite-Silica flour mixtures (100:0) (Martinez *et al.*, 2017) showed no plasticity and low electrical sensitivity. Calcium Carbonate Powder (Jang *et al.*, 2018; Jang & Santamarina, 2016) and Kaolinite-Silica flour mixtures (75:25) (Martinez *et al.*, 2017), Silt (Montoro & Francisca, 2017), and (Queensland) Land cover indicated no plasticity and intermediate electrical sensitivity. Meanwhile the electrical sensitivity to pore-fluid chemistry of the bentonite-kaolinite and kaolinite-silica floor mixtures increases with the bentonite and kaolinite fraction from intermediate plasticity and intermediate electrical sensitivity to high plasticity and high electrical sensitivity respectively, while that of kaolinite-silica floor mixtures increases from no plasticity, and low electrical sensitivity to intermediate plasticity and intermediate electrical sensitivity. Also important is the fact that the results on diatoms, silica silt, and mica shows that their behaviour are controlled by gravity rather than electrical interactions as a results of their relatively larger grain sizes (Jang *et al.*, 2018). This therefore means that the RSCS is capable of distinguishing the behaviour and transition of different systematic variations of binary mixtures from one classification group to another, a feature which is absent in the conventional soil classification scheme.

Furthermore, across the samples reviewed, none of the natural soils classify into low/no plasticity and high electrical sensitivity response group, whereas samples with intragrain porosity showed high plasticity but low electrical sensitivity, this was observed for Diatomaceous Earth (Schneider *et al.*, 2017), Diatomite (Bandini *et al.*, 2017), Diatom (Jang & Santamarina, 2016). Also, beyond specific surface areas, other properties of the soil samples appears to determine the plasticity and electrical sensitivity to pore-fluid chemistry; though all the smectite groups and, smectite dominated binary mixtures and intraporous samples classifies as high plasticity and high sensitive clays (Jang & Santamarina, 2016), yet other samples with equally high specific surface areas such as Diatomite (112 m^2/g) (Bandini *et al.*, 2017), Wollert basaltic clay (232 m^2/g); Mount Ridley basaltic clay (257 m^2/g); Braybrook basaltic clay (210 m^2/g); Arumpo bentonite (526 m^2/g); Melbourne Silurian Silty clay (80 m^2/g) (Narsilio *et al.*, 2017), Diatomaceous earth (103 m^2/g), Galveston, Texas clay (132 m^2/g) (Schneider *et al.*, 2017) did not classify into high plasticity and high sensitivity response group. This is due to the fact that, though the addition of high specific surface and very active clay mineral (smectite) alters the soil plasticity and electrical sensitivity to pore-fluid chemistry tremendously even in small proportions (Polidori, 2009; Schmitz *et al.*, 2004a), other factors such as pH, adsorbed cations, and level of crystallinity, surface charges and edge charges, capacity of the intragrain porosity to retain liquids, soil's aggregate nature and the pore fluid's dielectric constant all affects the soil plasticity (Spagnoli *et al.*, 2017). The aforelisted factors delineates the various changes in soil fabric and the consequent macroscale alterations (Ike *et al.*, 2023; Meegoda & Ratnaweera, 1994; Mishra *et al.*, 2012; Palomino & Santamarina, 2005). Furthermore, across the samples reviewed, none of the natural soils classify into low plasticity and high electrical sensitivity response group, that is either no plasticity and high electrical sensitivity or low plasticity and high electrical sensitivity whereas those with intraparticle porosity showed high plasticity but low electrical sensitivity (HL). Examples Diatomaceous Earth (Schneider *et al.*, 2017), Diatomite (Bandini *et al.*, 2017), Diatom (Jang & Santamarina, 2016).

Notwithstanding any prevailing factor, an increase in specific surface area largely stimulates the absorption of pore-fluids thereby increasing the liquid limit values and plasticity of the fine grained soils. For bentonites, high surface charge density in addition to high specific surface area precipitates more electrical interactions on the grain surface. The fundamental distinction between the smectite group and the other mineralogies is that smectite is predominantly controlled by variations in the thickness of double layer, which is equally dependent on both changes in ionic concentrations and electric permittivity of the permeant fluid (Ike *et al.*, 2023; Mitchell & Soga, 2005b), whereas edge charges and van der Waal forces (Ike *et al.*, 2023; Israelachvili, 2011; Santamarina *et al.*, 2002a) and/or fluid holding ability in the intergrain pore spaces influences the plasticity and electrical sensitivity to pore-fluid chemistry of the other samples. In this study, the fluid holding capacity was amplified by milling the sample using the high energy planetary milling technique, so as to enlarge the specific surface area.

Despite the great gains at redefining the existing soil classification system, there are yet knowledge gaps that needs to be filled; The revised fine-grained soil classification system (RSCS) relies on two fundamental properties; plasticity and electrical sensitivity of remolded samples to pore-fluid chemistry, and does not account for changes in soil properties due to evolution or diagenesis, such as weathering, erosion, aging, cementation, loading history and anthropogenic activities etc, as well as unusual soil properties that does not accurately fit into the plasticity and electrical sensitivity framework. The RSCS protocol therefore requires complementary in-situ testing so as to efficiently steer geotechnical decisions on soil properties. Also, the RSCS requires further standardization to ensure consistency across different laboratories and testing conditions; standard specifications or properties of the selected pore-fluids (such as kerosene, deionized water) and purity level of the materials used in preparing the pore-fluids (such as acids, bases and salts needed to prepare the brine solution) needs to be clearly defined, since these materials can be procured from different sources or brands or regions with possibly different compositions and standards which certainly will differ from those used in the original RSCS test protocol. Besides, the sample preparation techniques were not clearly defined, this is necessary because different procedures or sample treatments will have subtle or obvious influence on the outcome of the experiments, therefore specifying these conditions will be very important. Moreover, the sale of kerosene is highly regulated in some regions (like Pennsylvania (USA), India) while it is out rightly prohibited in others (Peru), even where they are not regulated or prohibited, drying the samples in conventional laboratory oven after conducting the test with kerosene can be very chronophagous (especially if the kerosene has heavier components) due to the low flashpoint of kerosene (65 – 85 ^{o}C), hence it becomes very pertinent to find better alternatives. Possible alternatives are the halogen moisture analyzer or the infrared moisture analyzer which are neater, faster, less expensive (especially the infrared moisture analyzer) repeatable and gives reliable results. As well, it is hazardous storing, handling and disposing some of the inflammable (kerosene) and toxic materials (such as acid and base for the brine solution) used in preparing the pore-fluids. Furthermore, the use of kerosene compacts the soil and forces kerosene unto the surface of the soil in the fall cone cup, this can adversely induce substantial variations in the plasticity and electrical sensitivity of soils in question. An alternative method is through the use of standard non-polar solvents with dielectric permittivity either similar to that of kerosene (κ' = 2) or between that of kerosene (κ' = 2) and 2 M NaCl (brine) solution (κ' = 55) as pore-fluids. Examples of such standard dielectric solvents and their dielectric constants are Decane-n (κ' = 2.0), Decyne (κ' = 2.2), Naphthalene (κ' = 2.3, 2.5), Xylene (κ' = 2.2), Nitroaniline-o (κ' = 34.5) etc. These standard options will not only eliminate the difficulty experienced in the use of kerosene as permeant fluid (Goodarzi *et al.*, 2016), but can indicate observable variations in the thickness of diffuse double layer that can demonstrate corresponding variations in the plasticity and electrical sensitivity of the soil to pore-fluid chemistry. Lastly, the threshold for electrical sensitivity to pore-fluid chemistry ($S_E = 0.4$ and $S_E = 1.0$) and plasticity test conducted with brine LL_{brine} (25 %, 50 %, 75 %, 100 %) appears to have been arbitrarily chosen, efforts should be made at having rationale behind the thresholds for each response groups

CONCLUSION

The Revised Soil Classification System (RSCS) addressed the weaknesses of the traditional classification system, especially by considering the particle-fluid interaction phenomenon, pore-fluid characteristics (pH, ionic concentration, and permittivity) and its impacts on soil behavior, the novel test protocol adopted liquid limit values of samples passing sieve number 200 (75 μm), used fall cone equipment in lieu of the imprecise Casagrande cup method to define the liquid limits, plasticity and the electrical sensitivity to pore-fluid chemistry. The permeant fluids used were electrically contrasting fluids; deionized water, 2 M NaCl solution and kerosene. Despite offering empirical description of fine-grained soil behaviour, the new classification scheme suffers some deficiencies. This study synthesized a vast collation of applicable and primary research findings, streamlined the perspectives, delineated the research gaps and made suggestions for further research. The current study will make for further improvement on the novel soil classification system necessary for effective and widespread application in geotechnical, geophysical and other geo-related applications. An effective understanding of the response of soil fabric in submerged conditions via an improved soil classification will ensure accurate assessment of the integrity and safety of underground constructions useful in solving environmental problems related to subsurface flow, sediment stability analyses, submarine excavation, engineered flow systems like groundwater pollutant movement and remediation, soil suitability assessment, soil aggregation, and stabilization, waste and barrier containment systems, hydrocarbon migration, resource recovery, and energy extraction applications.

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