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Impact of Clay Mineralogy and Dispersing Agents on Particle Size Analysis of Fine-Grained Soils

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ABSTRACT

Hydrometer analysis is a widely used method for determining the particle size distribution of fine-grained soils. However, its accuracy depends on assumptions of Stokes's law, and influence by other parameters such as temperature, type and concentration of dispersing agents and specific gravity etc. Furthermore, clay minerals exhibit distinct swelling and shrinkage behaviors, their interaction with dispersing agents directly influences sedimentation and particle size distribution. This study investigates how clay mineralogy influences the effectiveness of the dispersing agents and its implications for the classification of fine-grained soils. For the present study, six soil samples were analyzed for index properties (specific gravity, grain size distribution, free swell index, and Atterberg limits), chemical properties (pH and electrical conductivity), elemental composition (X-ray fluorescence), and surface charge (zeta potential). The findings reveal that conventional hydrometer analysis, which relies on assumed sedimentation behavior, often inaccurately represents actual mineralogical characteristics, underscoring its limitations. The results show that soil dispersion behavior varies considerably depending on mineral composition, as reflected by wide ranges in liquid-to-solid (L/S) ratios (2-50), pH (7.38-10.20), EC (0.027-0.522 mS/cm), and FSI (0-250%). Among the tested samples, sodium bentonite exhibited the highest dispersion efficiency, achieving a maximum zeta potential of (-48.7 mV). This study emphasizes the necessity of mineralogy-specific dispersion strategies to enhance the precision of fine-grained soil classification.

Keywords: Soil classification, Dispersing agents, Hydrometer analysis, Clay mineralogy.

INTRODUCTION

Accurate determination of Particle Size Distribution (PSD) is an essential aspect of fine-grained soil classification in geotechnical engineering, as it directly influences the understanding of soil behavior in terms of strength, permeability, and compressibility (Dascalu et al., 2022; Emeka, 2015). However, obtaining precise PSD results for clay rich soils is often challenging due to the combined effects of clay mineralogy and the dispersing agents used during testing (Abdulkarim et al., 2021). Clay minerals possess unique structural and chemical characteristics that significantly influence their behavior in sus-pension. Depending on the mineral type, soils may exhibit varying degrees of plasticity, cohesion, and susceptibility to flocculation (Emeka, 2015). These differences affect how particles interact with dispersing agents and settle during sedimentation-based analyses such as the hydrometer method (Arora, 2003). To address particle aggregation and ensure reliable measurement, chemical dispersants such as sodium hexametaphosphate and sodium carbonate are widely employed. These agents help to break apart soil masses by neutralizing inter particle attractions. However, the effectiveness of dispersants will not be uniform across all soil types (Abdulkarim et al., 2021; IS 2720 [Part 5], 1985; Kaur & Fanourakis, 2016). For instance, montmorillonite rich soils, due to their high swelling capacity and surface charge, typically require higher concentrations of dispersant for effective particle separation (Wintermyer & Kinter, 1955). In contrast, kaolinitic soils, which have a more stable and

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less reactive structure, disperse more readily with minimal treatment. Furthermore, several studies have demonstrated that both the type and dosage of dispersants can significantly influence the measured clay fraction (Wintermyer & Kinter, 1955). This, in turn, can lead to inconsistencies in PSD results. Additionally, comparisons between hydrometer and pipette methods have revealed notable discrepancies in grain size measurements (Bindu & Ramabhadran, 2010; IS 2720 [Part 4], 1985), further emphasizing the role of mineral dispersant interactions in test outcomes (Emeka, 2015; Odundun et al., 2023). Although standardized procedures are available, laboratory practices and regional guidelines still vary especially in the choice and amount of dispersant used. Additionally, traditional hydrometer analysis assumes that all fine-grained soils settle in the same way (Abdulkarim et al., 2021), However, this often overlooks the distinct mineralogical and chemical properties of different clay minerals, highlighting the growing need for customized dispersion methods tailored to their specific characteristics. Moreover, Stokes's law, which governs sedimentation rate of particles in a fluid, is significantly influenced by the viscosity of the suspending medium. Since viscosity is temperature dependent, even moderate changes in ambient temperature can alter the rate of particle settling. Higher temperatures reduce fluid viscosity, thereby increasing settling viscosity, while lower temperature have the opposite effects. In view of these considerations, the present study investigates the combined in-fluence of clay mineralogy and dispersing agents on the particle size distribution of fine-grained soils. Six soil samples with diverse mineralogical compositions were analyzed through a series of tests, including index properties (specific gravity, Atterberg limits, and free swell index), chemical characteristics (pH and electrical conductivity), elemental composition (X-ray fluorescence), and surface charge analysis (zeta potential). The findings highlight the limitations of conventional hydrometer methods and emphasize the importance of adopting mineralogy-specific dispersion protocols to improve the accuracy and reliability of fine-grained soil classification.

METHODS USED FOR THIS STUDY

The materials used in this study comprise six distinct types of fine-grained soils, namely Sodium Bentonite (NaB), Calcium Bentonite (CaB), Black Cotton Soils (BC1 and BC2), Red Soil (RS), and White Clay (WC), as illustrated in Fig. 1. These soils were selected to represent a broad spectrum of mineralogical compositions and plasticity behaviors relevant to geotechnical applications. Red Soil (RS), characterized by its relatively low plasticity and iron oxide content, was collected from the outskirts of Hyderabad, Telangana. Black Cotton Soils (BC1 and BC2), known for their high swelling potential due to montmorillonite dominance, were sourced from two geographically distinct locations Kollur and Isnapur within Telangana, to capture intra-regional variability. Sodium Bentonite (NaB) and Calcium Bentonite (CaB), both highly plastic clays but differing in cation exchange properties, were procured commercially from Genesis Rocks and Minerals Pvt. Ltd., ensuring consistency in mineralogical quality. White Clay (WC), with a kaolinitic mineralogy and low swelling capacity, was obtained from Vikarabad, Telangana.

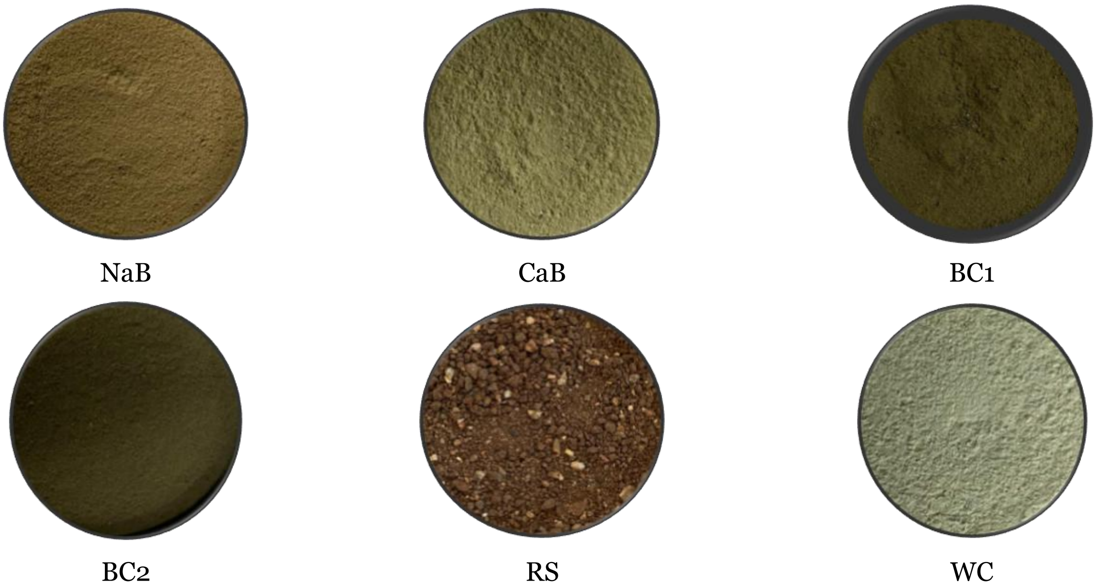

Fig.1. Fine-grained soils used for characterization.

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RESULTS AND DISCUSSION

To evaluate the physicochemical and plasticity characteristics of various fine-grained soils, an extensive laboratory investigation was conducted using specific gravity (IS 2720 [Part 3], 1980), hydrometer analysis (IS 2720 [Part 4], 1985), Atterberg limits (IS 2720 [Part 5], 1985), and free swell index tests (IS 2720 [Part 40], 1977).

Table 1. Properties of fine-grained soil

S. No	Type of soil	Specific gravity	Hydrometer analysis		Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Free swell index (%)
			Silt (%)	Clay (%)				
1	NaB	2.69	62	38	87.8	55.6	32.2	90
2	CaB	2.67	72	28	59.6	47.0	12.6	60
3	BC 1	2.74	75	25	57.0	35.6	21.4	70
4	BC 2	2.70	78	22	49.6	35.7	13.9	60
5	RS	2.62	89	11	25.4	23.9	1.5	20
6	WC	2.68	90.3	9.7	33.7	25.8	7.9	0

The specific gravity of the soil samples ranged from 2.62 to 2.74 (Table 1) (Won et al., 2021) indicating significant variations in mineralogical composition (Odundun et al., 2023; IS 2720 [Part 3], 1980). BC1 recorded the highest specific gravity (2.74), suggesting a major contribution of heavy minerals such as Iron (Fe), Aluminium (Al), and Silica (Si), which contribute to higher particle density. In contrast, RS exhibited the lowest specific gravity (2.62), likely due to a greater proportion of organic matter and a reduced concentration of dense mineral components. NaB (2.69), CaB (2.67), BC2 (2.70), and WC (2.68) showed similar specific gravity values, indicating consistent mineralogical composition and density. These variations in specific gravity not only reflect mineral composition but also significantly impact the settling the settling behavior of particles in sedimentation analysis. Soils that exhibit higher specific gravity generally settle more quickly, which directly affects the determined particle size distribution, particularly in techniques relying on gravitational separation such as hydrometer or pipette methods. Hence, recognizing the relationship between specific gravity and particle size distribution is essential for accurate interpretation of soil texture. To classify the fine-grained soils, hydrometer analysis was conducted, obtaining the relative proportions of silt and clay (IS 2720 [Part 4], 1985; Kaur & Fanourakis, 2016). The results revealed significant variations among the samples, attributed to differences in mineralogy as shown in Fig.2. BC1 exhibited the highest silt content (75%) and the lowest clay content (25%), suggesting a coarser texture that generally improves workability and reduces plasticity. In contrast, NaB had the highest clay content (38%) and the lowest silt content (62%), indicating a finer texture with higher plasticity and swelling potential. The other samples exhibited intermediate gradations: CaB (silt 72%, clay 28%), BC2 (silt 78%, clay 22%), RS (silt 89%, clay 11%), and WC (silt 80%, clay 20%), each reflecting varying degrees of fineness (Bindu & Ramabhadran, 2010). These variations in the silt to clay ratios highlight the influence of the parent material and environmental factors on the engineering properties of the soils. The consistency limits further highlighted the plastic nature of the soils (Rao, Reddy, Mohanty, & Reddy, 2021). NaB exhibited the highest liquid limit (87.8%) and plasticity index (32.2%) (Kaur & Fanourakis, 2016; Won at al., 2021), reflecting its high plasticity and significant water retention capacity due to its montmorillonite content. In contrast, CaB (LL 59.6%, PI 12.6%), BC1 (LL 57.0%, PI 21.4%), and BC2 (LL 49.6%, PI 13.9%) showed lower plasticity, suggesting a more balanced shrink-swell behavior. The free swell index (FSI) test, which assesses the swelling potential of soils, confirmed these trends (IS 2720 Part 40, 1977; Rao, Reddy, Mohanty, & Reddy, 2021). NaB had the highest FSI (90%), indicating strong expansiveness, while CaB (60%), BC2 (60%), and BC1 (70%) showed moderate swelling. RS exhibited low swelling (20%), and WC showed no swelling (0%). These results demonstrate that swelling behavior is influenced by clay content and mineral composition.

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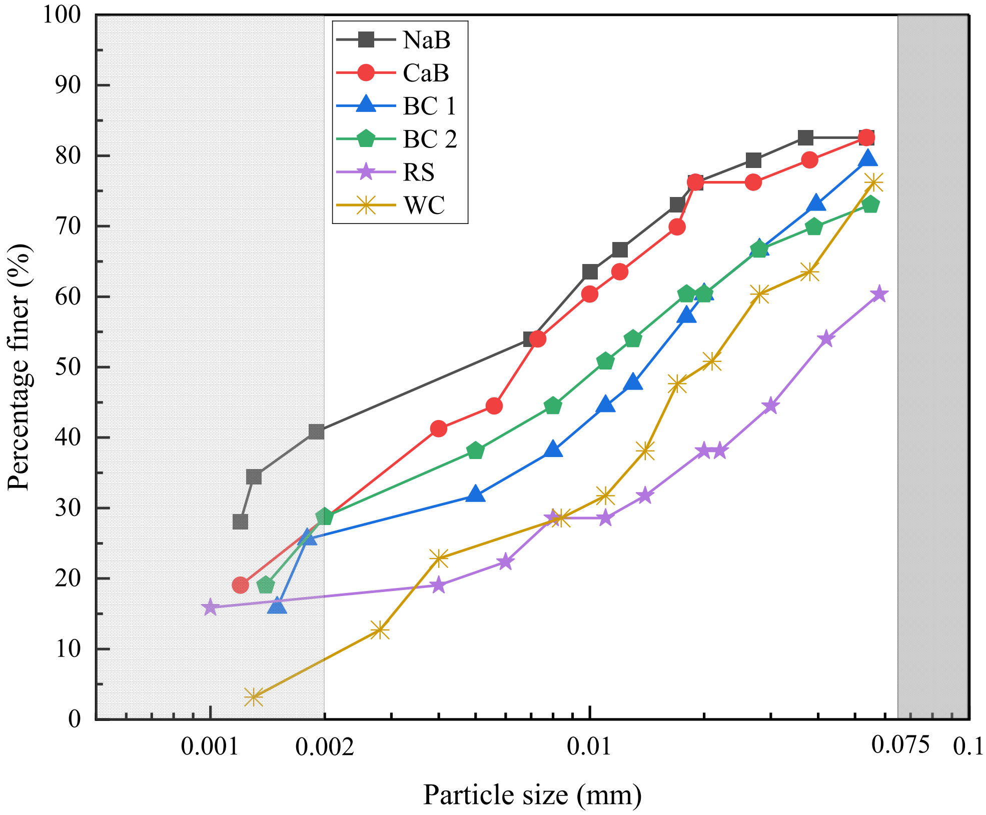

Fig.2. Depiction of hydrometer analysis results for different fine-grained soils.

INFLUENCE OF ELEMENTAL COMPOSITION AND ZETA POTENTIAL ON FINE-GRAINED SOIL PROPERTIES

To understand the influence of elemental composition and surface charge on the physical behavior of fine-grained soils, elemental analysis and zeta potential measurements were conducted (Table 2). Zeta potential, which reflects the electrokinetic potential at the particle-water interface, plays a crucial role in governing the interaction between soil particles and dispersing agents. Soils such as NaB and CaB exhibited highly negative zeta potential values, indicating strong inter particle repulsion; consequently, this was revealed in their higher free swell index (FSI) values, suggesting greater swelling potential due to enhanced dispersion (Rao, Reddy, Mohanty, & Reddy, 2021). On the other hand, WC displayed the least negative zeta potential, which resulted in minimal inter particle repulsion and, thus, a low FSI value, indicating limited swelling behavior. Elemental analysis showed that higher clay soils exhibited elevated levels of aluminum (Al), calcium (Ca), magnesium (Mg), and iron (Fe), enhancing their reactivity and plasticity (Dascalu, Owusu-Yeboah, Lungu, & Aniculaesi, 2022). Here, NaB showed high values of Fe (2.74%) and Ca (12.2%), aligning with its high FSI and LL. On the other hand, WC showed the lowest values of Fe (0.22%) and Si (43.0%), correlating with its stable behavior.

EFFECT OF LIQUID-TO-SOLID RATIO ON PH AND ELECTRICAL CONDUCTIVITY

To study the chemical response of soils under varying concentrations, the liquid-to-solid (L/S) ratio was varied from 2 to 50 (Table 3), and the pH and electrical conductivity (EC) were measured (IS 2720 Part 26, 1987; IS 14767, 2000). The experimental setup involved maintaining a constant volume of 100ml in test tubes, into which incremental soil masses (2, 4, 5, 10, 20, 25 and 50g) were added. This formulation of the L/S ratio provided a practical and consistent means to represent the relative concentration of soil within the solution, allowing systematic evaluation of pH and EC responses under dilution levels. The L/S ratio was varied from 2 to 50 to capture the chemical response of soils across a practical spectrum of dilution, encompassing both concentrated and moderately diluted suspensions. Extending the ratio be-yond 50 (i.e., using soil mass below 2g in 100ml suspension) was deliberately avoided due to multiple factors. At very high dilution levels, the resulting sus-pension becomes too weak to produce stable or

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measurable pH and EC values, often exceeding the sensitivity limits of standard pH and EC instruments. Additionally, excessive dilution may disrupt the dispersion stability by promoting particle aggregation and reducing the availability of exchangeable ions, thereby. Therefore, the chosen range of L/S ratios offers an optimal balance between experimental sensitivity and practical handling. All soils showed a trend of increasing pH with decreasing L/S ratio, attributed to the release of alkaline cations such as Ca2+ and Mg2+ from the soil structure. NaB and CaB displayed the highest increase in pH, reaching values above 8.9 at low L/S ratios as illustrated in Fig.3. In contrast, WC showed a relatively stable pH trend, with minor variation across different L/S ratios. This suggests a lower release

Table 2. Correlation of Zeta potential, Elemental composition and properties of fine-grained soils.

S. No	Type of Soil	Zeta Potential (-mV)	Elemental Composition							
			Si (%)	Al (%)	Ca (%)	Fe (%)	Mg (%)	K (%)	Ti (%)	Others
1	NaB	48.7	48.2	19.5	12.2	8.99	5.45	2.74	2.14	0.78
2	CaB	34.4	40.5	17.3	20.5	7.34	8.58	2.62	1.91	1.25
3	BC1	27.1	52.1	18.0	10.4	12.9	0.45	2.71	1.85	1.59
4	BC2	25.8	55.2	17.0	5.09	12.9	--	5.73	2.46	1.62
5	RS	21.1	69.3	11.4	3.59	5.0	--	6.95	1.81	1.95
6	WC	12.2	70.7	4.30	3.52	10.6	--	10.0	0.32	0.56

of basic cations due to its mineralogical stability. Similarly, RS maintained near neutral pH levels around 7.38, indicating low reactive potential. EC values generally decreased with increasing L/S ratios, as the concentration of free ions in the solution reduced (Fig.4). CaB exhibited the highest EC values, particularly at L/S = 2, reaching 0.520 mS/cm, owing to its high Ca content. WC, consistent with its low elemental content, recorded the lowest EC across all ratios (IS 14767, 2000). In the case of BC1, the observed dip in pH at an L/S ratio of 25 is likely due to a temporary suppression in the release of alkaline cations (Ca^{2+}, Mg^{2+}), reflecting a transitional state in ion exchange behavior. As the L/S ratio decreases further (i.e., more soil mass per unit liquid), enhanced dissolution and ion exchange increase the availability of these cations, leading to a rise in both pH and EC. Interestingly, the pH value of 9.51 was recorded at both L/S = 50 and L/S = 20, which may be attributed to a buffering phenomenon where the system resists further pH change due to the saturation of exchangeable cations. Despite this pH similarity, the EC values differ significantly. At L/S 20, the higher solid content results in greater ionic concentration in the suspension, thus increasinIn contrast, at L/S 50, the dilute nature of the solution reduces ion concentration, lowering EC. This contrast highlights that while pH may stabilize due to buffering effects, EC remains sensitive to total ionic strength and soil-to-water ratiosg EC. To illustrate the influence of water content on the chemical behavior of soils, Figures 3 and 4 present the variation in pH and electrical conductivity (EC) across different liquid-to-solid (L/S) ratios, highlighting an inverse relationship, where pH and EC values change remarkably with dilution levels. Soils with higher ionic content, such as CaB and NaB, exhibited significant fluctuations in EC, reflecting greater ionic mobility and solubility. In contrast, soils like WC and RS, characterized by lower soluble ion concentrations, maintained relatively stable EC values across all L/S ratios. These patterns underscore the critical role of elemental composition in governing the chemical responsiveness of soils to water content variations.

EFFECTS OF NAHMP INDUCED ALTERATIONS ON THE PHYSICOCHEMICAL PROPERTIES OF DIFFERENT SOIL TYPES

To determine the effectiveness of sodium hexametaphosphate (NaHMP) as a dispersing agent in hydrometer size analysis, a comprehensive evaluation was conducted on six fine grained soils, depend on effective dispersion to prevent particle aggregation and ensure accurate results (IS 2720 (Part 5), 1985; Odundun et al., 2023; Kaur and Fanourakis, 2016). In this study, NaHMP was exclusively employed to assess its impact on dispersion behavior, as it is known for its ability to disrupt electrostatic bonds between clay particles and maintain them in a suspended state (Dascalu et al., 2022; Odundun et al., 2023). Further, to systematically investigate this effect, a fixed soil mass (10 g)

Table 3. Influence of Liquid-to-Solid ratio on pH and Electrical Conductivity across soil types.

Type of soil	Tests	Liquid to Solid ratio (L/S)						
		50	**25**	**20**	**10**	**5**	**4**	**2**
NaB	pH	8.17	8.32	8.27	8.45	8.66	8.89	9.05
	EC (ms/cm)	0.045	0.065	0.075	0.109	0.160	0.186	0.236
CaB	pH	8.11	8.40	8.27	8.50	8.62	9.78	10.10
	EC (ms/cm)	0.060	0.072	0.100	0.259	0.342	0.491	0.520
BC 1	pH	9.51	9.29	9.51	9.98	10.20	9.96	10.16
	EC (ms/cm)	0.054	0.095	0.110	0.186	0.290	0.418	0.522
BC 2	pH	8.55	8.87	9.19	9.61	9.75	10.01	10.12
	EC (ms/cm)	0.050	0.055	0.080	0.110	0.145	0.243	0.370
RS	pH	7.38	7.55	7.75	7.96	8.02	8.00	8.45
	EC (ms/cm)	0.047	0.077	0.096	0.170	0.235	0.337	0.468
WC	pH	9.27	9.40	9.50	9.52	9.21	9.63	9.72
	EC (ms/cm)	0.027	0.0467	0.057	0.083	0.107	0.141	0.175

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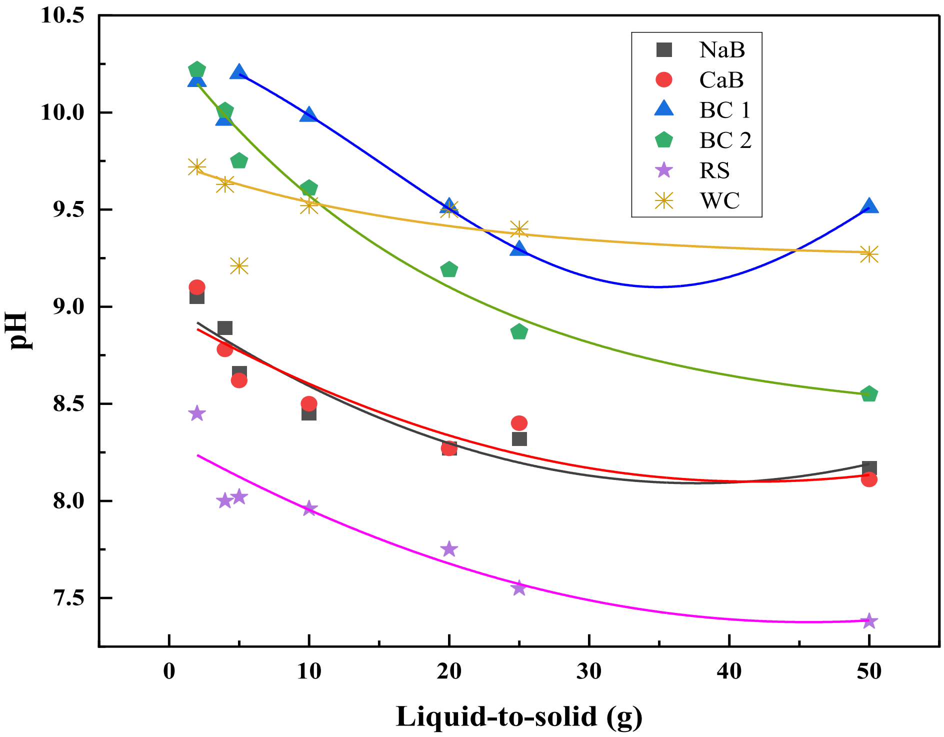

Fig.3. Variation of soil pH with varying Liquid-to-solid ratios for different types of soils.

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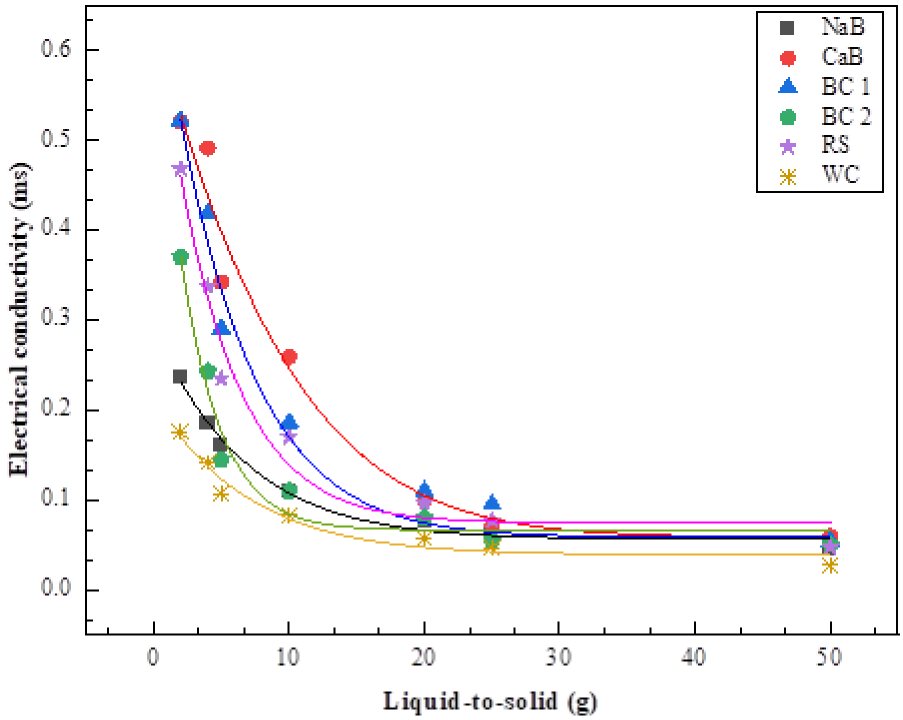

Fig.4. Variation of Electrical Conductivity with varying Liquid-to-Solid ratios for different types of soils

was treated with incremental doses of NaHMP (ranging from 0 to 7 g), and the resulting changes in pH, Electrical Conductivity (EC), and Free Swell Index (FSI) were recorded, as illustrated in Fig (5-7) and Table 4. Initial pH values varied across soils, with NaB and RS exhibiting more alkaline conditions, whereas BC1 and BC2 showed relatively lower values (Kaur & Fanourakis, 2016; IS 2720 (Part 26), 1987). Upon addition of NaHMP, all soils experienced a marked decline in pH, especially up to 3-5 g of dispersant, beyond which the pH trend stabilized as displayed in Fig.6. This behavior reflects the strong initial acidic influence of NaHMP and its diminishing effect at higher concentrations (Miller & Kissel, 2010). BC1 and BC2, in particular, showed a more gradual reduction in pH, suggesting a lower reactivity to the dispersing. Simultaneously, EC increased steadily with higher NaHMP amount across all soils, highlighting a consistent release of ions due to enhanced dispersion. CaB recorded the highest EC (21.8 mS/cm), followed by BC1 (19.66 mS/cm) and NaB (19.56 mS/cm), signifying their high ionic mobilities and exchange capacities as, shown in Table 4 (IS 14767, 2000; Tan et al., 2017).

In the standard procedure such as outlined in IS 2720 (Part 4), a combination of 33g sodium hexametaphosphate and 7g sodium carbonate, is recommended per liter of solution for effective particle dispersion. In the present study, the experimental volume was reduced to 10ml, hence the dispersant quantities were proportionally scaled down to 3.3g of sodium hexametaphosphate and 0.7g of sodium carbonate. Furthermore, to isolate the influence of sodium hexametaphosphate alone on dispersion behavior, only sodium hexametaphosphate was used in varying amounts (0-7g) providing a controlled understanding of its effect of particle deflocculation. In contrast, RS and WC exhibited smaller EC increases, consistent with their lower clay contents and limited ion exchange potential. The FSI results further illustrated the varying dispersion and swelling responses among the soils. NaB showed the highest FSI (250% at 4 g), suggesting high montmorillonite content and excellent water absorption (IS 2720 Part 40, 1977; Rao et al., 2021). BC1 and BC2 followed with peaks of 230% and 160%, respectively, showing moderate swelling potential as depicted in Fig.7. RS, with minimal clay content, exhibited only 40% maximum FSI, while WC remained largely non-expansive, reaching up to 20% FSI only at higher NaHMP doses (Table 4). These observations confirm that the effectiveness of NaHMP in dispersing fine particles is closely tied to the soil's mineralogical composition. Soils rich in expansive clays responded more significantly in terms of pH drop, ion release, and swelling behavior, whereas low-reactivity soils exhibited minimal change. Therefore, the study underscores the importance of considering both

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electrochemical and mineralogical characteristics when applying dispersants for soil classification and geotechnical analysis (Emeka, 2015).

Table 4. Impact of NaHMP addition on pH, free swell index and electrical conductivity in various soil types

Type of soil	Tests	NaHMP (g) 0	1	2	3	4	5	6	7
NaB	pH	8.70	5.84	5.59	5.49	5.34	5.59	5.48	5.36
	EC (ms/cm)	0.051	3.15	6.35	8.65	11.08	14.80	17.49	19.56
	FSI (%)	90	110	150	140	250	130	180	130
CaB	pH	8.75	6.55	6.42	6.18	6.27	5.88	5.86	6.02
	EC (ms/cm)	0.076	5.3	7.3	11.41	13.52	17.06	19.73	21.8
	FSI (%)	60	110	90	210	50	120	120	180
BC 1	pH	7.80	6.18	5.96	5.88	5.93	5.95	5.88	5.80
	EC (ms/cm)	0.018	3.40	6.50	9.33	11.92	13.88	15.30	19.66
	FSI (%)	70	150	200	180	190	230	200	180
BC 2	pH	9.33	7.15	7.03	6.94	6.93	6.82	6.81	6.77
	EC (ms/cm)	0.017	3.76	6.28	9.02	12.46	14.86	17.52	18.91
	FSI (%)	60	100	110	160	140	130	120	160
RS	pH	8.85	5.60	5.39	5.29	5.25	5.22	5.14	5.05
	EC (ms/cm)	0.037	4.06	6.85	9.63	12.02	14.40	16.00	17.79
	FSI (%)	20	40	20	30	30	40	40	10
WC	pH	9.01	6.13	5.93	5.71	5.69	5.66	5.58	5.60
	EC (ms/cm)	0.014	4.58	7.44	12.25	15.64	15.82	18.02	19.00
	FSI (%)	0	0	10	20	20	10	10	10

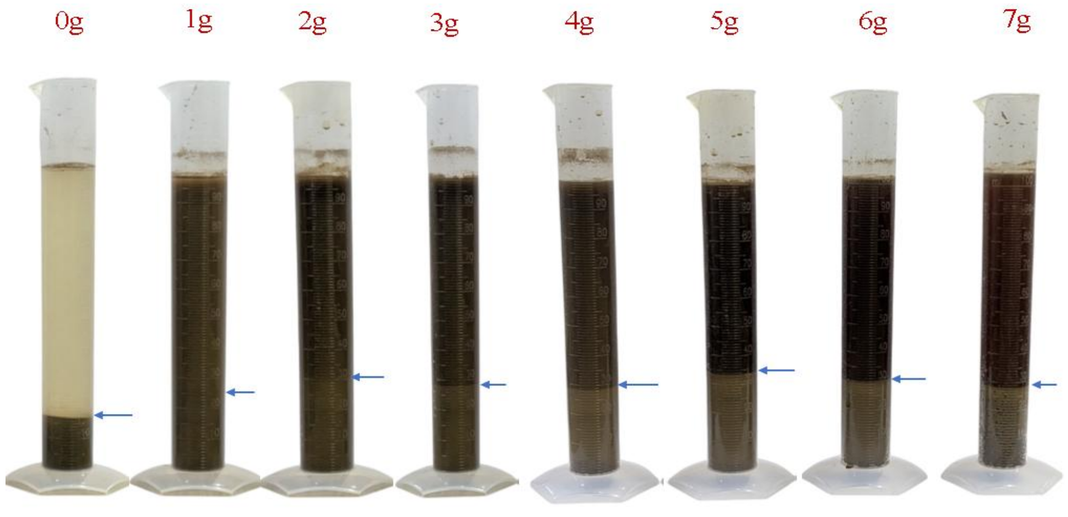

Fig.5. Evaluation of NaHMP Effects on BC1 Soil and Determination of Free Swell Index

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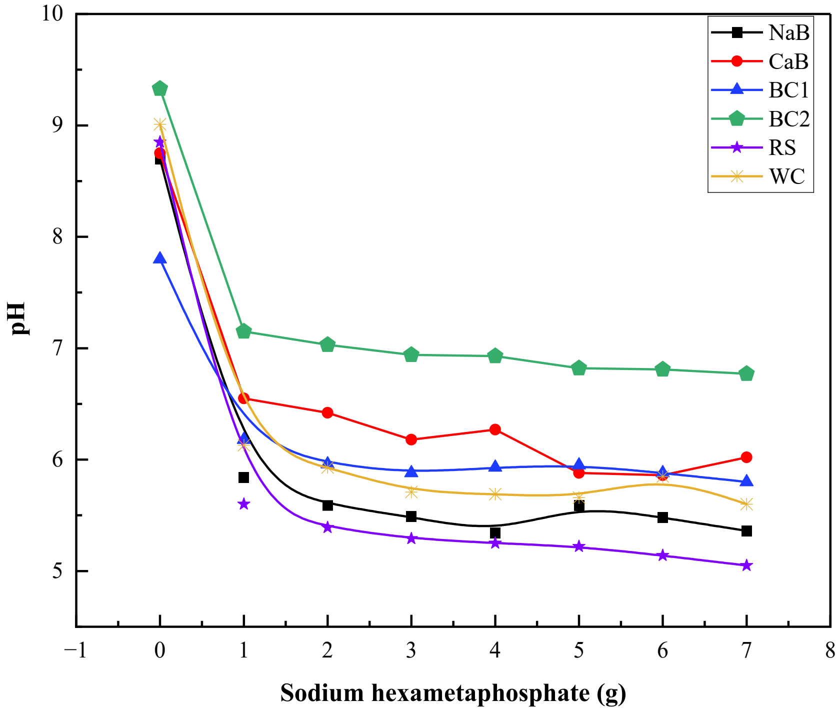

Fig.6. Effect of NaHMP on soil Ph

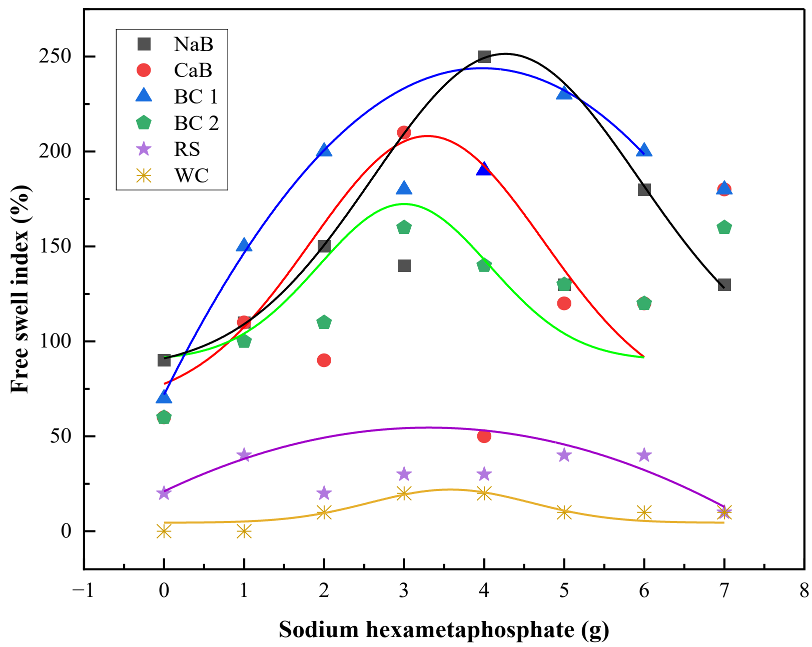

Fig.7. Effect of NaHMP on soil FSI.

CONCLUSIONS

The following conclusions were drawn from the study conducted:

1. The mineralogical composition of fine-grained soils plays a critical role in governing their dispersion and swelling behavior. Soils enriched with expansive clay minerals, such as NaB and CaB, demonstrated higher reactivity, reflected by elevated swelling indices and markedly negative zeta potential values.

2. Increasing NaHMP concentrations (0-7g) promoted dispersion, reflected by declining pH values and elevated EC values. These responses indicated intensifies ionic release and increased mobility of charged particles within the soil suspension

3. The variation in L/S ratio from 50 to 2 resulted in a general increase in pH, driven by the release of alkaline cations, though a slight drop was noted at L/S 25 for BC 1. Concurrently, EC values rose consistently as soil concentration increased, indicating elevated ionic strength. Identical pH values at L/S 50and 20, despite differing EC values, highlight the influence of buffering effects.

4. A strong correlation was observed among clay content, FSI and zeta potential. Soils that contained more clay content displayed more negative zeta potential values and increased FSI, confirming the influence of mineralogy and surface charge on swelling characteristics.

NOMENCLATURE

NaB	-	sodium bentonite
CaB	-	calcium bentonite
BC	-	black cotton soil
RS	-	red soil
WC	-	white clay
pH	-	hydrogen ion concentration
EC	-	electrical conductivity
NaHMP	-	sodium hexametaphosphate
FSI	-	free swell index
Ms	-	millie siemens

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