The Microstructure and Dispersive Characteristics of a River Nile Terrace Deposit from Northern Sudan

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Abstract

The microstructure of low plastic highly dispersive sandy silty clay (CL) deposit obtained from the terraces of the River Nile in Northern Sudan was studied using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) in relation to its dispersive characteristics. The study showed that the silt size of the CL is mostly aggregates of clay particles cemented by organic matter and iron oxide bonds. Kneading experiments have shown that these aggregates are unstable and could be broken by kneading and compaction. Pinhole tests on specimens prepared at wide ranges of density and water content and kept for different curing times (hours to one year) have shown that neither water content, density and curing times have pronounced effect on the dispersivity and erosion characteristics of the tested soil.

مستخلص

في هذه الورقة تمت دراسة التركيبة المجهرية لعينة تربة طينية تحتوي على الرمل والطمي عالية القابيلة للتفكيك تم جلبها من التروس العليا للنيل في شمال السودان وقد تمت الدراسة بإستخدام كل من حدود الأشعة السينية وإختبار المسح المجهري الإلكتروني. أوضحت الدراسة بأن الحبيبات في حجم الطمي عبارة عن حزم حبيبات طينية متماسكة بفعل مواد عضوية وأكاسيد الحديد كما وأوضحت إختبارات الخلط والعجن التي تمت يدوياً وبماكينة خلط التربة بأن هذه الحزم غير ثابتة وتتفتت بالدمك والعجن. أُجريت إختبارات للنحر بطريقة فتحة الأبرة على عينات تم تحضيرها بإختلاف كبير في المحتوى المائي والكثافة وحفظت لفترات مختلفة (بضع ساعات حتى سنة كاملة)، أوضحت هذه الإختبارات بأن محتوى الماء والكثافة ومدة الحفظ كل هذه العوامل لا تؤثر على قابلية التربة للتفتيت والنحر.

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1. Introduction

Soil dispersivity can be defined as the natural tendency of clayey soils to disperse (deflocculate) in the presence of water. Dispersive soils deflocculate easily and rapidly without significant mechanical assistance in water of low-salt content, therefore they are highly erodible. Problems associated with dispersive soils include gully erosion and failure of soil to perform adequately as a construction material. A dispersive soil does not lend itself to be identified by the range of conventional tests therefore some special tests have been developed in order to assess soil dispersivity. These can be divided into physical and chemical tests. The physical tests are concerned with the natural susceptibility of the soil to deflocculate in the presence of pure water. The most common physical tests used for this purpose are: the double hydrometer test and pinhole test. It has been ascertained that the presence of exchangeable sodium is an important factor contributing towards dispersive behavior in soils [1]. One of the main properties which also claimed to govern the susceptibility of clay to dispersion is the total content of dissolved salts in the pore water and the eroding water [1].

Dispersive soils are often tested in their natural condition. For double hydrometer and chemical tests a disturbed sample or a portion of it is tested or evaluated. The pinhole test evaluates the dispersive characteristics of a compacted soil sample prepared under standard Proctor density and water content. Since embankment materials may be placed under variable placement conditions, i.e. density and water conditions then the knowledge of the effects of these factors on the dispersive behavior of the placed soils is imperative. Few information is currently available on this issue [2], [3]. The raised queries are: is there a pronounced effect of compaction water content and dry density on soil dispersivity; and would prolonged curing causes any improvement to the dispersive behavior of soil materials known to be dispersive.

This paper attempts to provide responses to the raised queries by studying these factors for a potentially dispersive River Nile terrace deposit. The contribution of the microstructure of the soil and the effects of placement conditions such as density, water content and curing time on the dispersive behavior were investigated.

2. Study testing program

a. Nature and properties of soil material studies

The present study was undertaken on a soil material taken from a site located in the upper terraces of the River Nile at the Nile River Cataract No. 4 in the Northern State, Sudan where a large hydropower dam was built.

The project area lies in a rocky area and soils are found within the narrow flood plain of the river and/or in geologically recognized areas. The prevailing climate is desert with very long summer (March to November) and short winter (December to February). The day temperature in summer is close to 50 °C and the average annual precipitation less than 50 mm per year. Large amounts of earth core material were needed for the construction of the dam.

The soils prevailing at the study site are comprised mainly of heterogeneous alluvial silty clay believed to be formed through accumulation of sediments in an ancient river channel during high flood times and then drying out due to the very hot climate in the region. The soil is rarely wetted with the scarce rain water and is directly subjected to the intense solar heat.

Classification tests were carried out on the investigated soil in the laboratory to identify its type. The test results have shown that the soil is low plastic sandy silty clay and is classified as CL according to the Unified Soil Classification System (USCS); the liquid limit of the soil was found to be 41, the plasticity index is 15, the fines content is 61% and the clay content is

10%. Figure 1 shows sieve and hydrometer analysis of the studied soil with and without adding dispersant.

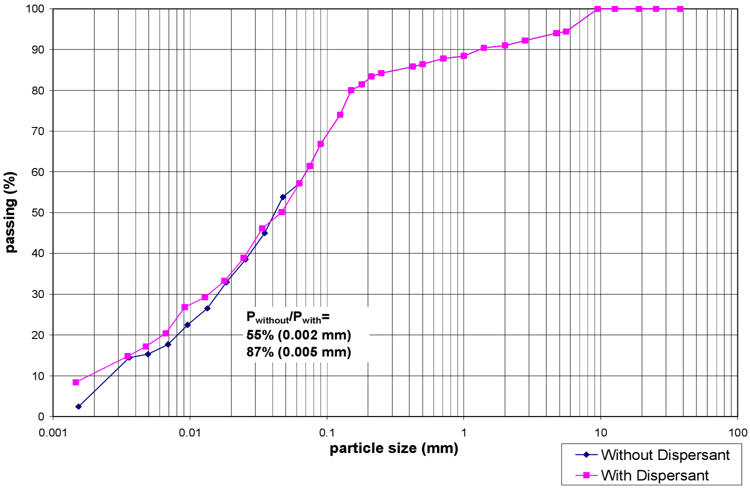

Fig. (1): Grain Size analysis of the CL soil with and without dispersant

b. Soil microstructure study

The testing program constituted microstructure analysis and observations to evaluate the effects of placement conditions (density and water content) on dispersivity.

The term "soil structure" comprises the fabric, composition and interparticle and bonding forces. The microstructure tests covered X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) to examine the microstructure and subsequently tests to study the effect on kneading and mixing on the microstructure.

Selected untreated specimens of samples representing the study area were subjected to the following special techniques:

- X-ray diffraction and chemical analysis for quantitative determination of the mineralogical constituents of the two samples. This also involved the determination of the cation exchange capacity (CEC) using the Cu-Trien method. In addition, the concentration of the exchangeable cation from the interlayer of the smectites was determined by Inductivity Coupled Plasma Optical Emission Spectroscopy. The tests were performed at the Division of Applied Mineralogy, University of Kalsruhe (TH), Germany.

- Observations in the scanning electron microscopy (SEM) of the soil fabric which is considered as an important component of soil structure and may be defined as the spatial arrangement of the soil particles, particle groups and the associated pore spaces [4]. Two principal levels of soil fabric have been generally recognized; the “macro or visual” level and the “micro or non-visual) level. The former can be observed with the naked eye or hand lens but the latter requires the use of some form of soil micromorphology technology such as the scanning electron microscopy (SEM). The SEM instrument was employed in this study to examine the most important micro-fabric features in natural and treated specimens of the study soil considered.

c. Soil dispersion study

The dispersion tests were performed to confirm the dispersive behavior of the studied soil [5]. The dispersion tests performed included the double hydrometer (Figure 1), pinhole and chemical test methods. All the three test methods confirmed that the soil material is highly dispersive.

A comprehensive test program was implemented to study the effects of soil placement conditions such as density, water content and curing time on the dispersion behavior of the soil material. The pinhole testing method was selected as the main tool for testing the dispersive behavior and erodibility of the tested specimens and was considered suitable for this laboratory study because its results are reproducible and remolded specimens with varying moisture contents and densities can be prepared and tested.

The pinhole test procedure intended to study the effects of water content, density and curing time on the dispersive behavior of the soil is described hereunder:

- The soil sample was divided into six subgroups designated as G1 to G6. Each group was prepared at the same moisture content and dry density (Table 1). More than six identical test specimens were prepared from each group for pinhole testing. The adopted dry densities were either 88% or 95% or 105% of the Standard Proctor MDD, while the adopted moisture contents were in the range of (OMC-4.3) % to (OMC+3.7) %. The actual water content and density conditions applied to the samples are given in Table (1). The remolded specimens are representative of a compacted material in an earth embankment or core material of an embankment dam.

- The preparation of specimens was started by screening of the material through a 2 mm size sieve. The material was carefully screened through the sieve and stored inside plastic bags to prevent drying out of the material, after which the moisture content was adjusted to the required moisture content. For preparation of specimens, a special two half-cylinder mould having internal dimensions similar to the pinhole test specimen, connected with removable clip to allow easy removal of the remolded specimen was manufactured. Specimens were prepared by filling in the mould in five equal layers with calculated weight of soil for each layer to obtain the specified dry density and moisture content. Each prepared specimen was either immediately pinhole tested or was sealed in plastic bags and stored for the assigned curing period before testing. The curing time reflects the time before exposure to flowing water, i.e. first water filling of reservoir.
- One specimen from each group was pinhole-tested immediately after preparation and after 6 hours, 1 day, 3 days, 7 days and 1 month.
- As a consequence of analysis of the results of the originally planned work, it was deemed useful to prepare some additional specimens for more curing times. Another group of specimens was added to test moisture content at optimum and wet of optimum with higher dry density of 101 % and 105% of MDD. These specimens were tested after more than one year of curing.
- All specimens were pinhole tested after the planned curing times were attained. The specimens were identified after the test to one of the grades of the pinhole test: D1 (highly dispersive), D2 (dispersive), ND4 (moderately dispersive), ND3 (slightly dispersive), ND2 (very slightly dispersive) and ND1 (non dispersive).
- For this dispersive soil and for such a wide range of water content (about 4% above and below OMC) and for the different densities, the soils were found to be dispersive. All the samples were reported as D1 (highly dispersive according to the pinhole rating).

Table 1: The Selected water contents and dry densities for sample preparations

Sample CL				
OMC 21.3; MDD 16.3 KN/m^3				
Sample	**MC (%)**		**DD (KN/m^3)**	**% of MDD (KN/m^3)**
1	17	OMC-4.3	16.91	105%
2	17	OMC-4.3	15.32	95%
3	21	~OMC	16.91	105%
4	21	~OMC	15.32	95%
5	21	~OMC	14.19	88%
6	25	OMC+3.7	15.32	95%

3. Analysis and discussion of the study results

a. X-ray analysis and SEM microfabric results

The diffraction and chemical analysis carried out on representative sample [6] have shown that the dominant clay minerals within the CL sample were smectite (~20-30 %), muscovite (~8%), Kaolinite (~6%), chlorite (~5%) and zeolite (~3%). Diffraction and spectroscopy analysis have shown that the smectites of the CL sample were mainly sodium saturated (Figure 2).

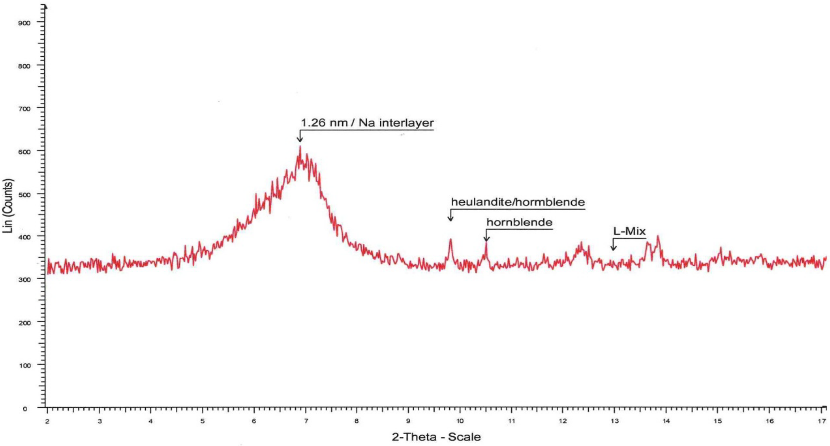

Fig. (2): X-ray diffraction diagram of the CL and ML soils

The soil micro-fabric features observed in the SEM electronic micrographs shown in Figure 3 on the specimens of the sample examined indicated that the soil fraction of the CL was consisting of assemblages or aggregations coagulated/conglutinated of finest (clayey) particles (Figure 3). Soil particle assemblages are units of particle organization formed by arrays of various elementary particle arrangements. Clay aggregations are assemblages which act effectively as individual units or flakes. They are generally regular or rounded to sub-angular in shape and up to the sand particles in size. Aggregations may be divided into two sub-forms; simple and compound. A simple aggregation may comprise a single or any combination of elementary clay arrangements whereas a compound aggregation is made of two or more simple aggregations packed close to each other so that they appear to act as one unit.

Treatments of natural specimens of the CL soil with H_2O_2 to remove organic matter and dithionite to remove iron hydroxide and oxide have shown breakage of the aggregates to relatively smaller sizes due to removal of organic matter and iron oxide bonds for the CL soil.

b. Dispersion testing by pinhole method

Based on the micro-fabric evaluation of the CL soil, it was decided to check the stability of the fine aggregates by kneading the soil by hand and in an electric mixer for varying time spans and then performing Atterberg limits and grain size distribution by the sieve and hydrometer test methods to examine the change in plasticity and gradation caused by the manual and mechanical mixing.

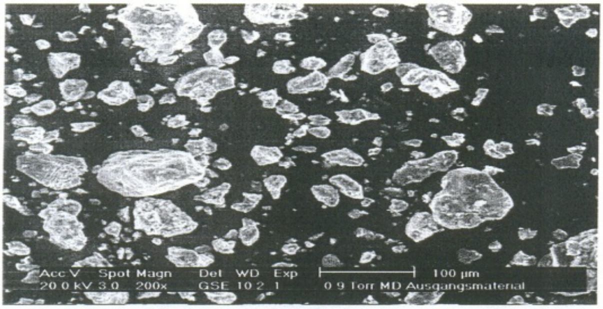

Fig. (3a) SEM micrographs showing the microfabric features of natural untreated CL soil material

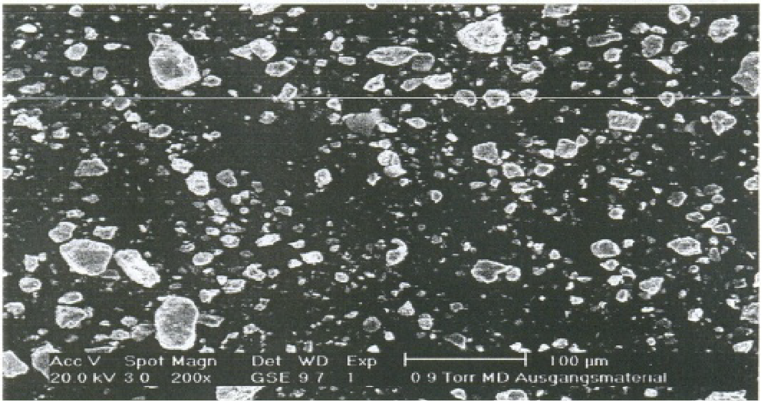

Fig. (3b) SEM micrographs showing the microfabric features of natural untreated CL soil material treated with H_2O_2 to remove organic matter

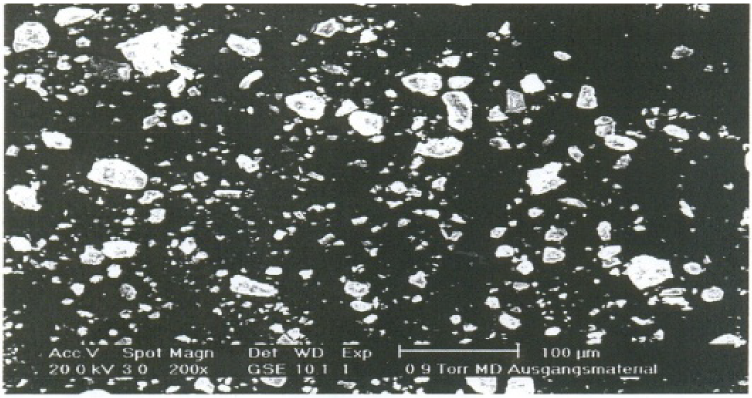

Fig. (3c) SEM micrographs for CL samples treated with H_2O_2 and dithionite to remove iron hydroxide

Table (2) lists a summary of these soil classification test results which were subsequently plotted in Figures 4 and 5 to illustrate the effects of kneading effort and time on soil plasticity and gradation respectively.

Table 2: Summary of Atterberg limits and gradation test results for manual and mechanical kneading of the CL soil.

Kneading Effort	Kneading Time (hours)	Atterberg limits (%)			Soil gradation (Percent finer than)	
		L.L	P.L	P.I	Fines content (FC) %	Clay content (CC) %
Manual	0	41	26	15	61	10
	0.5	44	25	19	59	8
	1.0	46	24	22	57	9
	1.5	48	24	24	60	11
Mechanical	0	41	26	15	61	10
	1	53	23	30	62	13
	3	66	24	42	64	19
	5	63	22	41	68	26

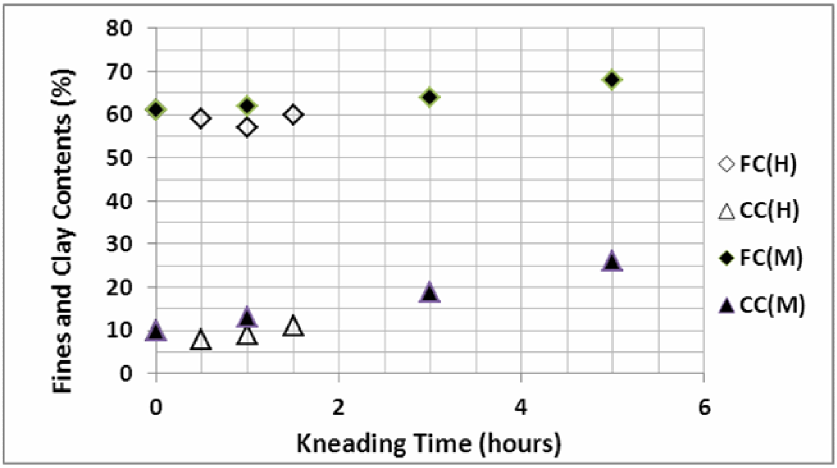

Fig. (4) Effect of time of manual (hand) and mechanical soil kneading on the gradation properties of CL soil

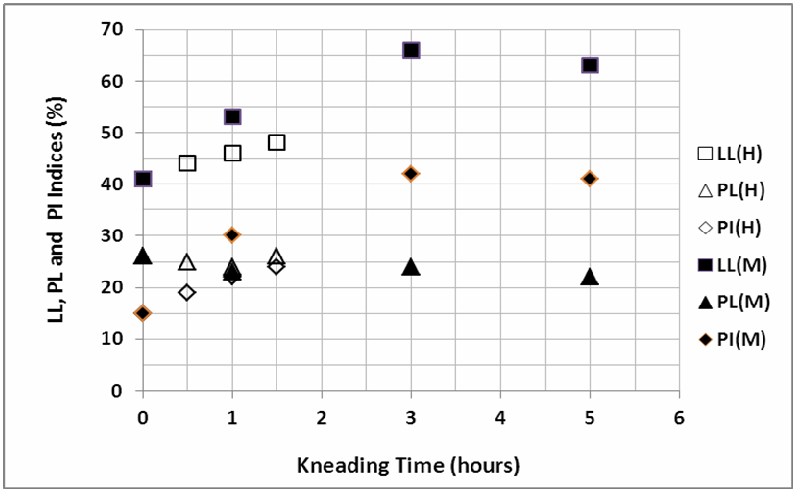

Fig. (5) Effect of time of manual (hand) and mechanical soil kneading on the plasticity indices of CL soil

As noted from the data in Table 2 and the trends in Figures 4 and 5, there were significant increases in the liquid limit amounting to 17% upon subjecting the soil to one hour of manual kneading and to 54% upon subjecting the soil to 3 hours of mechanical kneading. The corresponding increases in soil plasticity index amounted to 60% and 173% for the soil samples subjected to the same time durations of manual and mechanical kneading respectively. The trends shown in Figure 4 indicate slight reductions in the liquid limit and plasticity index values upon subjecting the soil to mechanical kneading exceeding 3 hours whereas such reductions were not noted for the soil sample subjected to up to 1.5 hours of manual kneading. The grain size distribution test results in Table (2) and Figure (5) show that the manual and mechanical kneading caused no or insignificant changes (less than 13%) in the fine content (fraction passing No. 200 test sieve) of the soil. However, the mechanical kneading caused a substantial increase in the clay content reaching 160% with time up to three hours of mixing compared to initial value pertaining to the untreated soil sample.

The mechanical and manual kneading compaction experiments clearly indicate that the aggregates of the CL soil are unstable and could be altered by kneading compaction. The kneading effort was able to break the aggregation caused by organic and iron bonding as suggested by the SEM fabric micrographs shown in Figures 4 and 5. The very small change in the fines content is an indication that the aggregates which were broken by kneading were within the silt size.

The results of the pinhole testing for the soil specimens, with no exception, indicate that they were highly dispersive for all curing times. Therefore, observations of the micro-fabric features in the SEM and the results of the kneading tests have shown that the apparently looking as silt particles of the CL soil are partly formed of aggregation of clay particles bonded together with iron hydroxides and organic matter. The manual and mechanical kneading efforts applied to specimens of the soil for different time durations are believed to have caused breakage of larger sized aggregates to smaller sized ones. The substantial increase in the clay content fraction of the original untreated soil upon mechanical kneading supports this hypothesis and indicate that the larger aggregates ‘silt size’ are composed of assemblages of many smaller clay aggregations. Since these soil aggregates are naturally unstable then they could be easily broken up by the flow of water through them. Therefore, the high degree of dispersivity indicated by the results of the pinhole testing for the studied clay soil may be attributed, partly, in the microstructure level, to the instability of the aggregates forming the CL soil.

c. Effects of compaction placement conditions and curing time on the dispersivity of CL soil

It is recalled here that the pinhole tests results have shown that for the different densities and water contents and for curing times up to one month, the tested specimens were found to be dispersive. All the samples were reported as D1 (highly dispersive according to the pinhole rating).

In order to investigate whether some improvement in the erosion resistance could take place after longer curing periods, tests were performed on the specimens stored for longer period of time before being pinhole tested. After more than one year of curing these specimens were pinhole tested and the results were still dispersive as they were before, except that a minor change in the result for the specimen prepared at the highest dry density using the OMC was exhibited. This change was from highly dispersive to dispersive, which could be considered as very minor change with no real significance in the erosion resistance behavior. However, it may indicate that more improvement can be expected for very long curing periods especially if cured under loaded condition.

4. Conclusions

The present study was undertaken on a low plastic clay soil taken from a site located in the upper terraces of the River Nile where a large hydropower dam was built in Northern Sudan. This paper attempts to explain the highly dispersive phenomenon and investigates the main factors influencing the behavior of the studied soil deposit. The contribution of the microstructure of the soil and the effects of placement conditions such as density, water content and curing time were investigated.

A study program comprising microstructure analysis and dispersion testing was considered and executed. The microstructure analysis covered X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) whereas the pinhole method was selected for testing and evaluation of the soil dispersive behavior and erodibility.

The soil micro-fabric features observed in the SEM indicated that the soil fraction of the CL soil was comprised of aggregates coagulated/conglutinated of clay particles. Treatments with H_2O_2 and dithionite have shown breakage of the soil aggregates to smaller sized ones due to the removal of organic matter and iron oxide/hydroxide bonds for the CL soil.

The soil microstructure analysis, SEM microfabric observations and kneading experiment results clearly indicate that the highly dispersive behavior of the CL soil may be attributed to the weak bonds between the aggregations constituting the main soil structure features composed of assemblages of smaller clay aggregations. Since the aggregates assemblages in the original soil are naturally unstable then they could easily be broken up by the flow of water through them. Such a speculation is supported and manifested by:

i. The observations of the micro-fabric features in the SEM have shown that the apparently looking as silt particles of the CL soil are partly formed of aggregation of clay particles.

ii. The breakage of soil aggregate assemblages into sub-aggregates due to kneading efforts applied to specimens for different time durations resulting in substantial increases in the clay content and plasticity of the untreated soil.

The study results showed that the variations in the soil compaction placement conditions i.e. moisture content and dry density and curing time did not produce reduction in the high dispersion potential of the CL soil or improvement in its erosion resistance. Soil specimens prepared at OMC and the highest dry density or subjected to prolonged curing times after compaction exhibited no or negligible changes in the dispersion potential of the CL soil with no real significance in its erosion resistance behavior.

Acknowledgement

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5. References

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