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Synthesizing an Artificial Loess for Geotechnical Investigations of Collapsible Soil Behavior

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***Abstract*—**Collapsible soils like loess comprise an important category of problematic soils for construction purposes and sustainable development. As a result, research on both geological and geotechnical aspects of this type of soil have been in progress for decades. However, considerable natural variability in physical properties of in-situ loess strata even in a single block sample challenges the fundamental laboratory investigations. The reason behind this is that it is somehow impossible to remove the effect of a specific factor like void ratio from fair comparisons to come with a reliable conclusion. In order to cope with this limitation, two types of artificially made dispersive and calcareous loess are introduced which can be easily reproduced in any soil mechanics laboratory provided that all its compositions are known and controlled. The collapse potential is explored for a variety of soil water salinity and lime content and comparisons are made against the natural soil behavior. Trends are reported for the influence of pore water salinity on collapse potential under different osmotic flow conditions. The most important advantage of artificial loess is the ease of controlling cementing agent content like calcite or dispersive potential for studying their influence on mechanical soil behavior.

***Keywords*—**Artificial loess, unsaturated soils, collapse potential, dispersive clays, laboratory tests.

I. Introduction

LOEES is a special type of soil originating from an aeolian geological formation process, resulted in a considerably loose packing of soil grains [1]. Moreover, precipitation of cementing agent into the natural soil strata has formed a metastable structure provided by weak bonding between particles. The cementing agent can be soluble [2] or insoluble [3] in water such as sodium chloride or calcite, respectively. Any alteration of external hydraulic or mechanical boundary conditions could hence result in smoothening or breakage of inter-particle bonding and the consequent collapse of soil structure is inevitable [4]. The collapse phenomenon, best representing the natural loess, has been vastly reported in the literature as the triggering mechanism for catastrophic landslides. In addition, serviceability of manmade structures constructed on natural loess layers was severely influenced by collapse of soil structure [5], [6]. As collapse of loess strata can be both fatal and costly, it is therefore very crucial to critically investigate the influence of both soluble and insoluble bonding agent on collapse potential and appropriate consultancy can be provided for optimized ground improvement [7].

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Although collapsibility of loess is an issue of great importance, there are difficulties in exploring natural loess behavior. First of all, field exploration and in-situ testing are costly [8] and limited to very specific ground and hydro-mechanical loading conditions for a particular site. Second, high quality sampling such as block sampling technique is the minimum requirement, which is both costly and in need of technical expertise at research level. Most importantly, natural variability of soil conditions such as void ratio, water, or cement content can be considerably high even in a block, making a fair comparison very difficult [9]. In addition, bonding agent is predetermined and site-specific and may not be varied to other desired levels for studying its influence on loess collapsibility.

In order to avoid difficulties in dealing with natural loess, the idea of artificial loess has been put forward by various research groups worldwide [10]-[12]. Some research focused on the formation process to be as close as possible to the natural aeolian origin [10], [11]. The role of bonding agent has been purely limited to the adhesion provided by clay minerals distributed among silt particles, while true cohesion provided by a cementing agent such as calcite has been ignored. On the other hand, natural loess was considered as the base soil for reproducing artificially structured loess with additional calcium oxide and subsequent chemical reactions [12]. The limitation is the existence of unknown amount of calcite in the parent soil and hence the independent evaluation of calcite effect on collapsibility may not be feasible. In addition, most of these studies targeted at reproducing artificial calcareous loess, while very few effort has been made to consider the role of impure pore water on collapsibility of dispersive loess [6]. Therefore, the main objective of current study is to introduce two artificially structured dispersive and calcareous loess mimicking two naturally occurred clayey and silty loess, respectively. In addition, a preliminary study is carried out on introduced artificial loess to explore the role of both water salinity and lime content on collapsibility. Results are eventually compared against those obtained from tests on target natural loess and the observed differences are discussed.

II. Experimental Procedure

A. Different Types of Natural Loess and Test Materials

Loess was classified according to [13] under three categories of sandy, silty, and clayey loess. This classification is mainly based on particle size distribution and plasticity characteristics of the soil under consideration. It is noted that occurrence of silty and clayey loess are dominant in this classification. Loess can also be categorized according to the bonding agent between soil particles. The cohesion between silt and sand particles may be provided by clay minerals [14], calcite bonding [3], crystalline salt under unsaturated conditions [6], or a combination of them. In order to have the most optional choices at hand, two types of natural silty and clayey loess were considered as target materials for reproduction. The former was retrieved from Golestan loess deposits [15] and the latter was obtained from Mokran coastline nearby Chabahar international port in Iran [6]. In addition, the Golestaln silty loess is mainly calcareous, while the clayey loess occurred in Chabahar region is dispersive.

Artificial loess were therefore benchmarked against these two types of natural loess by considering three main criteria. The criteria considered are particle size distribution, plasticity properties and collapse potential. More important, commercial and reproducible standard geomaterials were used in artificial loess reproduction. The geomaterial components utilized include the industrial Firuzkuh sand/silt/clay-sized particles, bentonite, and kaolin. Firuzkuh is a standard non-plastic soil retrieved from Firuzkuh mine. The soil is grinded to different sizes ranging from clay-sized to coarse sand and is commercially available under different codes with specific size gradation. Results obtained from a variety of sieve analyses, hydrometer tests, and Atterberg limits revealed that Firuzkuh No. 181 & Micronized are the best non-plastic constituent representing natural loess characteristics. The percentage of all non-plastic and plastic components for reproducing artificially made clayey and silty loess is given in Table I.

TABLE I
TYPES OF SOIL COMPONENTS USED IN ARTIFICIAL LOESS

Type	Clayey loess	Silty loess
Firuzkuh No. 181 (%)	15	8
Firuzkuh No. Micronized (%)	65	66
Bentonite (%)	20	10
Kaolin (%)	0	16

B. Particle Size Distribution and Aterberg Limits

The particle size distribution curves of natural clayey and silty loess are indicated in Fig. 1. According to the first criterion established, the best combination of soil constituents was obtained (Table I) following a trial and error approach so that the best possible match between natural and artificial curves be established. It should be also noted that particle size distribution was considered in conjunction with plasticity chart (Fig. 2). In other words, both criteria are considered concurrently to satisfy plasticity characteristics and particle size distribution as close as possible to those of the target natural loess. As shown in Fig. 1 (a), an excellent match was established for the clayey loess and a relatively satisfactory match can be found between particle size distribution curves of natural and artificial silty loess (Fig. 1 (b)).

Fig. 2 compares the plasticity index against liquid limit for natural and artificial loess. Moreover, three regions related to the classification proposed by [13] based on plasticity information are plotted for the sake of comparison. The artificial clayey loess was divided into two types of dispersive and non-dispersive loess as the target material was reported to be a clayey loess with distinct dispersive potential. Results confirm the clear influence of water salinity on alteration of plasticity properties. However, data of both artificial dispersive and non-dispersive loess as well as that of natural dispersive loess lie in the clayey loess region [13]. In addition, plasticity properties of natural and artificial silty loess are also well within the boundary of silty loess. It can be therefore concluded that artificially made clayey and silty loess can well mimic the natural soil properties in terms of both particle size distribution and plasticity specifications.

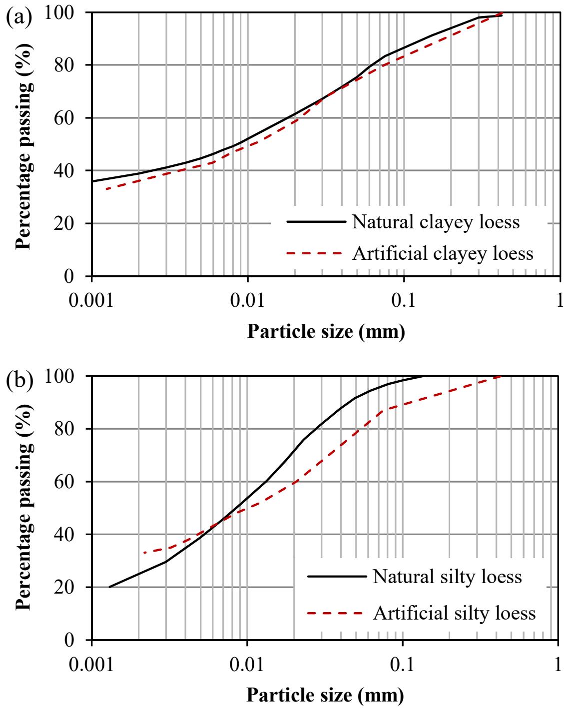

Fig. 1 Particle size distribution of natural and artificial (a) clayey, and (b) silty loess

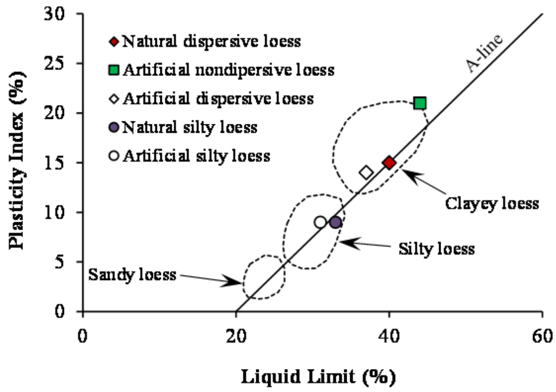

Fig. 2 Plasticity chart of natural and artificial loess in comparison with three common types of loess [13]

C. Soil Classification

Physical soil properties were measured and summarized in

Table II for the four types of test materials considered according to the ASTM standards. Index soil properties were used to classify the studied soils according to the unified soil classification system (USCS). Both natural and artificial loess are classified as low plasticity fine-grained soils.

TABLE II
PHYSICAL PROPERTIES OF NATURAL AND ARTIFICIAL LOESS

Property	Clayey loess		Silty loess	
	Natural	Artificial	Natural	Artificial
Summary of Particle Size Distribution				
Sand Content (%)	16	20	3	13
Silt Content (%)	45	44	74	55
Clay Content (%)	39	36	23	32
Atterberg Limits				
Liquid Limit (%)	40	44	33	31
Plastic Limit (%)	25	22	24	22
Plasticity Index (%)	15	22	9	9
Compaction characteristics				
Maximum Dry Density (kg/m^3)	1650	1820	-	-
Optimum Water Content (%)	21.2	17.6	-	-
Soil Classification				
USCS	CL	CL	CL	ML

D. Sample Preparation and Test Program

The natural dispersive clayey loess retrieved from Chabahar area was artificially reproduced with and without dispersive potential. One intact specimen was obtained from a block sample taken from a test pit [2] to determine the in-situ characteristics of natural dispersive loess. In order to examine the influence of dispersive potential on collapsibility, one artificial specimen was mixed with distilled water and the other with 4 M sodium chloride solution to the target water content and left in a sealed plastic bag overnight for moisture equalization. Accordingly, the two artificial loess specimens were statically compacted inside the oedometer ring at a constant rate of 1 kg/min to the target dry density and water content corresponding to the field values of 1153 kg/m^3 and 14%, respectively. Three collapse potential tests were carried out on the specimens following the ASTM D5333 with distilled water as inundation fluid. In addition, the role of osmotic flow direction was investigated through conducting collapse tests on four artificial specimens. All these specimens were compacted to a higher dry density of 1500 kg/m^3 and 14% water content. The compaction water content used in preparing soil-water admixture was distilled water for the two specimens and 4 M sodium chloride solution for the other two. Each set of specimens were inundated inside the oedometer cell with both distilled and saline water with the same molality used in sample preparation. As a result, it is possible to explore the role of osmotic flow on loess collapsibility under no flow, inward (with relation to the specimen), and outward flow conditions. In summary, seven tests were carried out for dispersive and non-dispersive artificial and natural loess.

Artificial calcareous silty loess were reproduced following the method proposed by [12]. Test specimens were prepared by mixing the base artificially reproduced silty loess with four levels of calcium oxide by weight including 0%, 2%, 5%, and 9%. The specimens were therefore compacted inside a triaxial mold to the target dry density and water content of 1600 kg/m^3 and 14%, respectively. Fig. 3 represents a schematic diagram of test configuration for preparation of calcareous loess. The compacted specimens were wrapped in a latex membrane and were sandwiched between two sets of consecutive filter paper and porous stone. According to (1), distilled water was circulated from bottom to top of the specimens for 24 h so that calcium hydroxide will be formed. Water circulation was afterwards followed by percolation of carbon dioxide from the same path, resulted in the formation of calcite bonding between soil particles (2). The synthesized specimens were eventually air dried and trimmed to fit the oedometer ring. The same collapse testing protocol as in the case of dispersive loess was followed by utilizing distilled water as the inundation fluid for the four tests conducted. In conclusion, a total of 11 collapse potential tests were carried out to explore the influence of dispersive potential and lime content on collapsibility.

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{1}$$

$$Ca(OH)_2 + CO_2 \rightarrow Ca(CO)_3 + H_2O \tag{2}$$

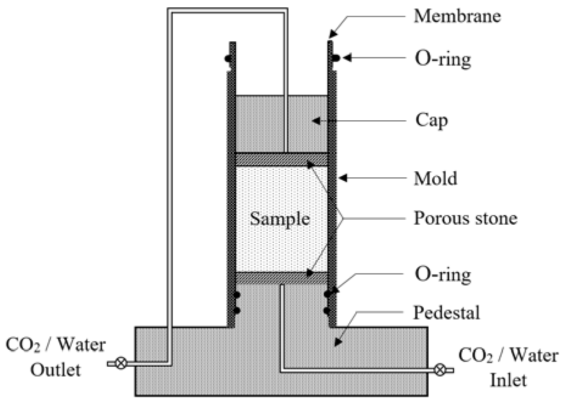

Fig. 3 Experimental setup for preparation of artificially made calcareous loess

III. TEST RESULTS

Results of tests are interpreted based on collapse potential. The collapse potential is defined as the change in volumetric strain due to water saturation under 200 kPa vertical surcharge. The mathematical expression can be written as:

$$C_p = (e_{com} - e_{con}) / (1 + e_0) \tag{3}$$

where C_p is collapse potential, e_0 is the initial void ratio, e_{com} is the void ratio delivered after constant-water compression under 200 kPa vertical stress, and e_{con} is the after consolidation void ratio achieved after inundation stage under the same stress level.

A. Dispersive Loess

Fig. 4 compares the collapse potential of natural dispersive loess with two artificially made dispersive and non-dispersive loess. Results show that collapsibility of three specimens tested is very high in the range corresponding to the soils with “severe trouble” for construction purposes according to the criteria proposed by [16]. There are, however, some differences in measurements. The intact natural loess has the highest collapsibility while the artificial dispersive loess shows the lowest amount of collapse potential. The reason for the relatively higher collapse potential of intact loess may be attributed to the more non-uniform distribution of voids and the existence of a larger macropore population compared to the other two recompacted specimens [17]. Regarding collapsibility of the artificial loess, it is evident that compaction pore water salinity reduces the collapse potential. The observed drop in collapse potential may arise from the reduction in the thickness of diffuse double layer with pore water salinity [2]. As a result, the dispersive loess shows less inclination towards volume contraction upon wetting compared with the non-dispersive one.

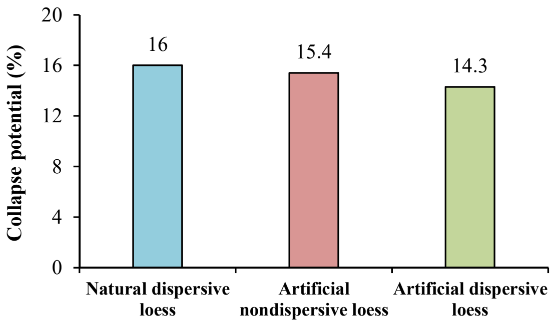

Fig. 4 Comparison of artificially made loess with the natural dispersive one in terms of collapse potential

Collapsibility was also investigated for artificial loess with and without dispersive potential for different osmotic flow regimes. Results of Fig. 5 reveal a significant reduction in collapsibility with a rise in salinity of inundation fluid. In other words, the highest collapse potential is expected to occur if both dispersive and non-dispersive loess are inundated with distilled water. More importantly, collapse potential is consistently higher for tests conducted under no osmotic flow compared to those carried out with inward or outward osmotic flow. In addition, the influence of osmotic flow on collapsibility reduces as salinity of inundation fluid increases.

B. Calcareous Loess

Fig. 6 indicates variations in collapse potential with lime content for the artificially made calcareous silty loess. Results confirm a clear influence of calcite cementation on reduction in collapse potential. Collapsibility reduces with a rise in lime content at a reduced rate, implying the marginal stiffening effect of calcite bonding towards higher lime content. It can be inferred that high amount of calcite would not provide further inter-particle bonding to counteract collapse-induced by wetting, but this extra lime content simply fills in the voids. Result of collapse potential for the natural calcareous loess is also plotted for comparison [15]. Results of Fig. 6 indicate a significantly higher collapse potential for intact loess compared with the artificial one. The observed difference could be mainly attributed to the existence of extra-large pores in the intact structure, delivering a higher collapsibility as in the case of dispersive loess. It is also noted that the lime content for the intact loess was simply obtained from [18] since no direct measurements were conducted to quantify it.

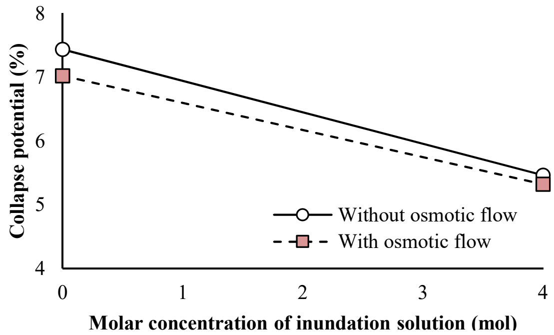

Fig. 5 The influence of NaCl solution concentration on collapse potential with and without osmotic flow

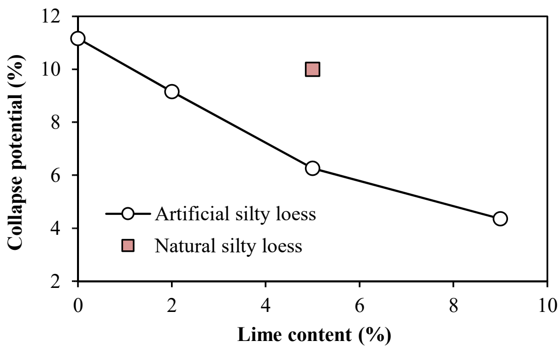

Fig. 6 Variations in collapse potential against lime content for artificially made calcareous loess

IV. Discussion

New trends for variations in collapse potential with salinity of inundation fluid at different osmotic flow regimes were characterized and reported. Some of the results were interpreted based on the influence of pore water salinity on the thickness of diffuse double layer and hence collapse potential. Although dispersive potential can be a governing factor controlling the amount of potential collapse due to wetting, a few tests were run to support this finding. Indeed, a more comprehensive test program is required to address this issue.

Regarding both artificially made loess, there is still one important issue of difficulties in simulating the intact structure. The intact structure of natural loess has been formed during years under complex field conditions including but not limited to loading or unloading, wetting-drying cycles, temperature fluctuations, agricultural activities and so forth.

Therefore, it is very important to bear in mind the significance of loess microstructure on dominating soil behavior from small strain phenomena [19] to large strain characteristics [20] and water retention properties [21].

V. CONCLUSION

The current study aimed at artificially reproducing two common types of dispersive and calcareous loess for exploring fundamental soil behavior under controlled laboratory conditions. The products were benchmarked against two types of natural clayey and silty loess occurred in the North and Southeast of Iran, respectively. Although the natural clayey loess was reported to contain significant amount of sodium chloride, the silty loess was observed to be almost calcareous. Therefore, the influence of different salinity and calcite cementation on collapse potential of two artificially made loess was investigated. Results were also compared against natural behavior of base soils. It was observed that general trends in collapse potential versus salinity and lime content can be obtained satisfactorily by examining the artificial loess. However, comparisons made against natural loess revealed that microstructure of in-situ loess may not be simply simulated in laboratory due to the formation of intact structure under complex field conditions and existence of so many interacting variables such as wetting-drying cycles, temperature fluctuations, cyclic freezing-thawing, creep phenomenon, etc. Such influencing factors are mainly absent for sample production under laboratory conditions unless they are specifically simulated and considered.

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