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Influence of Matric and Osmotic Suction on the Collapse Potential of Semi-Arid Loess in Western India

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Abstract

Collapsible loess deposits in semi-arid regions present significant geotechnical challenges due to their sensitivity to moisture fluctuations. This study investigates the hydro-mechanical behavior of loess soil from Chandwaji, Rajasthan, by characterizing its suction properties across a range of moisture contents from dry-of-optimum (OMC-4%) to wet-of-optimum (OMC+4%). Using the filter paper method (ASTM D5298-10), both total and matric suction were measured to decouple the contributions of capillary and osmotic forces to the soil's stability. The results demonstrate a profound reduction in soil energy potential upon wetting: Total suction decreased from 2,287 kPa at OMC-4% to 22.2 kPa at OMC+4%. A critical transition was observed at the OMC-2% state, where matric suction dropped sharply to 116 kPa while total suction remained high at 903 kPa, revealing that osmotic suction (787 kPa) becomes the dominant stabilizing force (87% contribution) in this transition zone. This finding suggests that the collapse mechanism in semi-arid loess is driven not only by the loss of capillary tension but also significantly by the dissolution of soluble salts. The study highlights the necessity of accounting for both suction components in settlement prediction models, as neglecting the osmotic component may underestimate the collapse potential of soils in arid environments.

Keywords: Collapsible soil, Loess, Filter paper method, Matric suction, Osmotic suction, Soil-water characteristic curve (SWCC).

1. Introduction

1.1 Background

Collapsible soils, characterized by a metastable structure, pose severe risks to civil infrastructure in arid and semi-arid regions globally. These soils typically exhibit high apparent strength and stiffness in their natural dry state but undergo rapid volume reduction (collapse) upon wetting, often without any increase in external load (Jennings & Knight, 1975). Loess, a wind-blown silt deposit, is the most prevalent collapsible soil, covering extensive areas of China, the United States, Europe, and parts of Western India.

In the semi-arid regions of Rajasthan, India, loess deposits are frequently encountered. These soils are subjected to extreme seasonal moisture variations, remaining desiccated for most of the year before undergoing rapid saturation during the monsoon season. This cyclic wetting poses a significant hazard to foundations, canals, and road embankments.

1.2 Theoretical Framework

The mechanics of collapsible soils are best understood through the framework of unsaturated soil mechanics. Fredlund and Morgenstern (1977) proposed that the behavior of unsaturated soil is governed by two independent stress variables: net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$. However, total suction (ψ) comprises two distinct components:

$$\psi = (u_a - u_w) + \pi$$

Where $(u_a - u_w)$ is matric suction (derived from capillary and adsorptive forces) and π is osmotic suction (derived from dissolved salts in the pore water).

1.3 Research Gap and Objective

While matric suction is widely recognized as the primary contributor to the shear strength of unsaturated soils, the role of osmotic suction is often neglected in standard geotechnical practice. In semi-arid environments like Rajasthan, where high evaporation rates lead to salt accumulation, osmotic suction can be significant. This study hypothesizes that "apparent strength" in these soils is heavily influenced by osmotic forces. The objective of this research is to experimentally decouple the matric and osmotic suction components of Indian loess using the filter paper method and to evaluate their respective evolutions during the wetting process.

2. Materials and Methods

2.1 Site Description and Material

The soil used in this investigation was obtained from a known loess deposit in Chandwaji, Rajasthan (Coordinates: 27°14.313'N, 75°56.840'E). The samples were collected from a depth of 1.5 m to ensure the retrieval of representative sub-soil material. The site is located in a semi-arid climatic zone characterized by high evaporation rates and distinct wet-dry cycles.

2.2 Soil Characterization

Standard laboratory tests were conducted to determine the index and engineering properties of the soil in accordance with Indian Standards (IS 2720). The soil is classified as Low Plasticity Silt (ML) with a specific gravity of 2.68. The summary of index properties is presented in Table 1.

Table 1: Index and Engineering Properties of the Soil

Property	Value
Specific Gravity (G_s)	2.68
Liquid Limit (LL)	30%
Plastic Limit (PL)	20%
Plasticity Index (PI)	10%
Optimum Moisture Content (OMC)	12.8%
Maximum Dry Density (MDD)	1.86 g/cc
Soil Classification (USCS)	ML (Silt)

2.3 Experimental Program: Suction Measurement

The filter paper method was selected for suction measurement due to its ability to measure the entire range of suction (0 to 100,000 kPa) and its capability to distinguish between total and matric suction (ASTM D5298-10).

2.3.1 Sample Preparation

Remolded specimens were statically compacted to the Maximum Dry Density (MDD) at five distinct moisture contents: OMC-4%, OMC-2%, OMC, OMC+2%, and OMC+4%. This range was selected to simulate the wetting path of the soil from a desiccated state to near-saturation.

2.3.2 Testing Procedure

Whatman No. 42 ash-less filter papers were used as passive sensors.

- **Total Suction Measurement:** Filter papers were placed in a non-contact configuration (suspended above the soil specimen) to allow vapor equilibration.
- **Matric Suction Measurement:** Filter papers were placed in direct contact with the soil (sandwiched between three papers, with the center paper used for measurement) to allow capillary equilibration.

The soil-paper systems were sealed in air-tight glass jars and placed in a temperature-controlled environment ($25°C \pm 1°C$) for a period of 7 to 10 days to ensure thermodynamic equilibrium. Following equilibration, the water content of the filter papers was determined using a high-precision balance (0.0001g accuracy), and suction values were calculated using the standard bi-linear calibration curves provided in ASTM D5298.

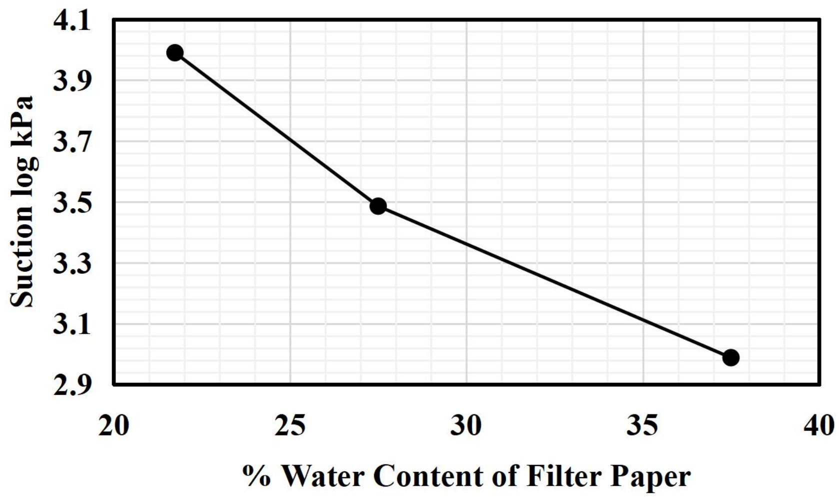

Figure 1: Filter paper calibration curve for Whatman No. 42. Relationship between filter paper water content and total suction using NaCl solution calibration. The bi-linear relationship enables conversion of filter paper water content measurements to suction values for soil samples

Figure 1 illustrates the calibration relationship established for the Whatman No. 42 filter paper batch used in this investigation. The data points exhibit a strong correlation with the standard bi-linear model prescribed by ASTM D5298, confirming the thermodynamic equilibrium of the closed-system setup. This calibration curve serves as the fundamental transfer function for converting the gravimetric water content of the passive sensors into soil suction values, ensuring that subsequent measurements of total and matric potential remain within the reliable range of the instrument

3. Results

3.1 Calibration Verification

Prior to testing, the calibration of the Whatman #42 filter paper batch was verified using NaCl solutions of known molality. The calibration data followed the standard bi-linear relationship, ensuring the accuracy of subsequent soil measurements.

3.2 Suction Characteristics

The variation of total and matric suction with moisture content is summarized in Table 2 and visualized in Figure 1.

Table 2: Summary of Measured Suction Components

Moisture Condition	Total Suction (kPa)	Matric Suction (kPa)	Osmotic Suction* (kPa)
OMC - 4%	2,287.1	1,697.1	590.0
OMC - 2%	903.9	116.4	787.5
OMC	242.2	52.6	189.6
OMC + 2%	53.3	52.5	0.8
OMC + 4%	26.2	26.1	Negligible

**Calculated as Total Suction - Matric Suction*

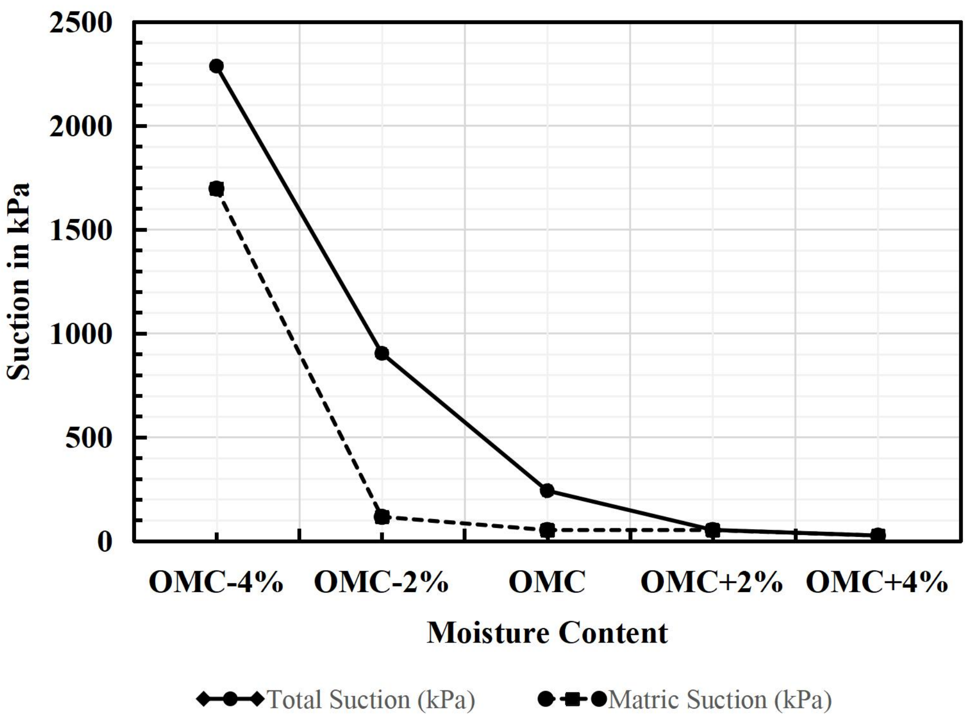

Figure 2: Variation of total and matric suction with moisture content. The soil exhibits high suction potential in the dry state (OMC-4%), with a sharp reduction in matric suction at OMC-2% (116 kPa) while total suction remains elevated (903.9 kPa), indicating the dominance of osmotic suction. Both components converge to low values near saturation (OMC+4%)

The Soil-Water Characteristic Curves (SWCC) for both total and matric suction are presented in Figure 2. A distinct hysteresis is observed between the two energy potentials; while both curves follow a logarithmic decrement with increasing moisture, they exhibit significant divergence in the dry-of-optimum range. Specifically, the matric suction collapses rapidly—dropping by an order of magnitude between OMC-4% and OMC-2%—whereas the total suction retains a high residual value. This disparity highlights the presence of a secondary suction component that sustains the soil's energy potential even as capillary menisci relax

3.3 Component Decomposition

The data reveals three distinct phases in the suction-moisture relationship:

1. **Dry Phase (OMC-4%):** At high suction levels, both matric (1,697 kPa) and total (2,287 kPa) suctions are significant. Capillary forces in the micropores are the dominant mechanism, contributing approximately 74% of the total energy potential.
2. **Transition Phase (OMC-2%):** A sharp divergence occurs as moisture increases to OMC-2%. Matric suction drops precipitously to **116 kPa**, indicating the relaxation of capillary menisci in larger pores. However, total suction remains high at **903 kPa**. Consequently, osmotic suction becomes the dominant component, contributing **87%** of the total suction.
3. **Wet Phase (OMC+):** Beyond the optimum moisture content, both suction components converge to low values (<60 kPa). At OMC+4%, the osmotic component vanishes (~0 kPa), likely due to the dilution of pore fluid, and matric suction stabilizes at a residual value of 26 kPa.

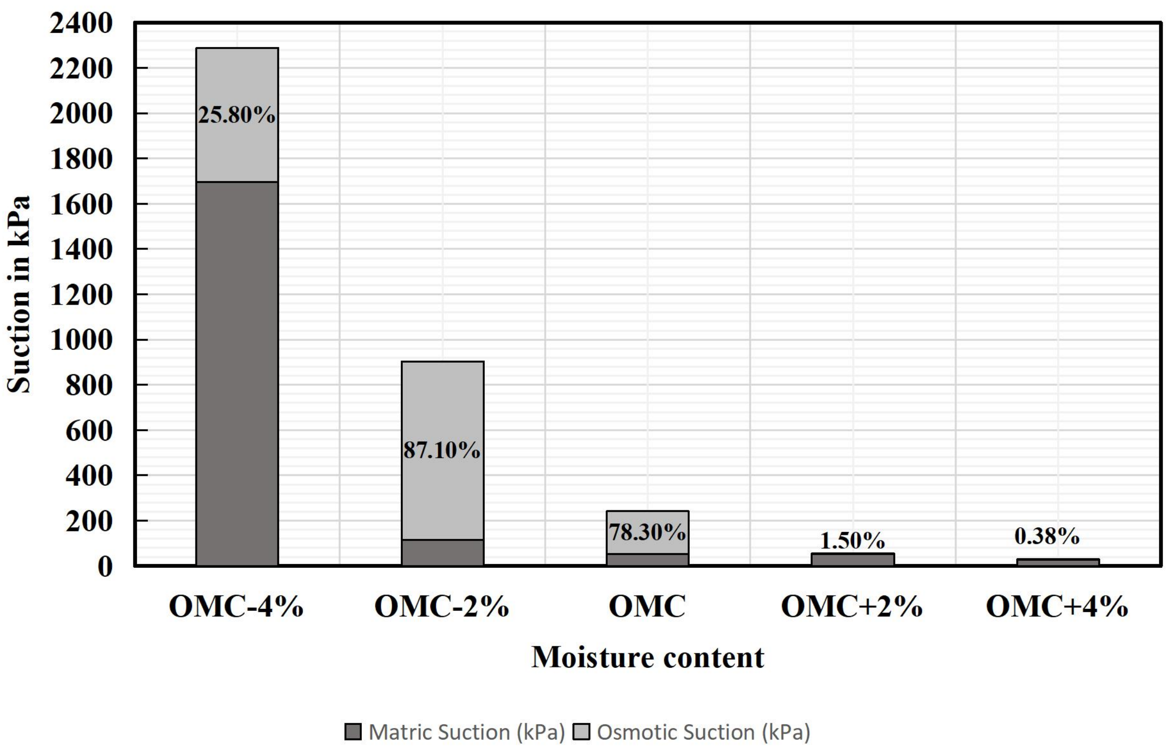

Figure 3: Decomposition of total suction into matric and osmotic components. Osmotic suction peaks at 87.1% of total suction at the OMC-2% condition, highlighting the critical role of dissolved salts in maintaining the soil structure. Upon further wetting (OMC+2% and beyond), osmotic suction decays rapidly due to salt dilution

To quantify the distinct contributions of capillary and chemical forces, Figure 3 decomposes the total suction into its matric and osmotic constituents across the wetting path. The analysis reveals a critical inversion in suction dominance at the transition zone (OMC-2%). At this moisture state, the osmotic component is not merely supplementary but dominant, accounting for 87.1% of the total soil water potential. This visualization challenges the conventional assumption that matric suction is the sole governing parameter in unsaturated loess, suggesting instead that the soil's apparent strength is heavily reliant on pore-fluid chemistry during the initial stages of wetting

4. Discussion

4.1 Mechanisms of Suction Loss

The experimental results highlight the non-uniform decay of suction components. Matric suction is highly sensitive to the initial wetting phase; a moisture increase of just 2% (from OMC-4% to OMC-2%) caused a ~93% reduction in matric suction. This confirms that the capillary network in loess is fragile and easily disrupted by the introduction of moisture.

In contrast, osmotic suction persists longer during the wetting process. At OMC-2%, the osmotic suction actually appeared to peak (787 kPa). This phenomenon may be attributed to the mobilization of salts into the pore water before sufficient water is available to dilute the solution concentration.

4.2 The Role of Osmotic Suction in Collapse

The decoupling of suction components at the transition zone (OMC-2%) offers critical insight into the collapse mechanism of Indian loess. In classic unsaturated soil mechanics, wetting-induced collapse is attributed solely to the reduction of effective stress as matric suction dissipates. However, the data suggests a **dual-mechanism failure** for this deposit:

1. **Initial Wetting:** As the soil wets to OMC-2%, the capillary "bridge" between particles weakens (Matric drop), but the soil structure is temporarily maintained by the high chemical potential of the pore fluid (Osmotic dominance).
2. **Critical Saturation:** As wetting continues towards saturation (OMC+), the pore fluid dilutes, causing the rapid decay of osmotic suction.

This implies that engineering designs relying on matric suction measurements alone may dangerously overestimate the stability of the soil. The "salt strength" provided by osmotic suction is transient; it resists failure during minor moisture fluctuations but vanishes completely during monsoonal saturation, leading to sudden and severe settlement.

Figure 4 traces the decay profile of osmotic suction, offering insight into the chemo-mechanical instability of the soil structure. The curve demonstrates a non-linear decay, characterized by a peak mobilization at OMC-2% followed by a rapid dissolution phase. This behavior implies that the stabilizing 'salt bridges' within the soil matrix are transient; they maintain structural integrity during minor moisture fluctuations but dissolve almost instantaneously upon approaching saturation (OMC+2%). Consequently, the loss of this chemical bond serves as a precursor to the hydro-mechanical collapse often observed in these deposits during monsoonal events.

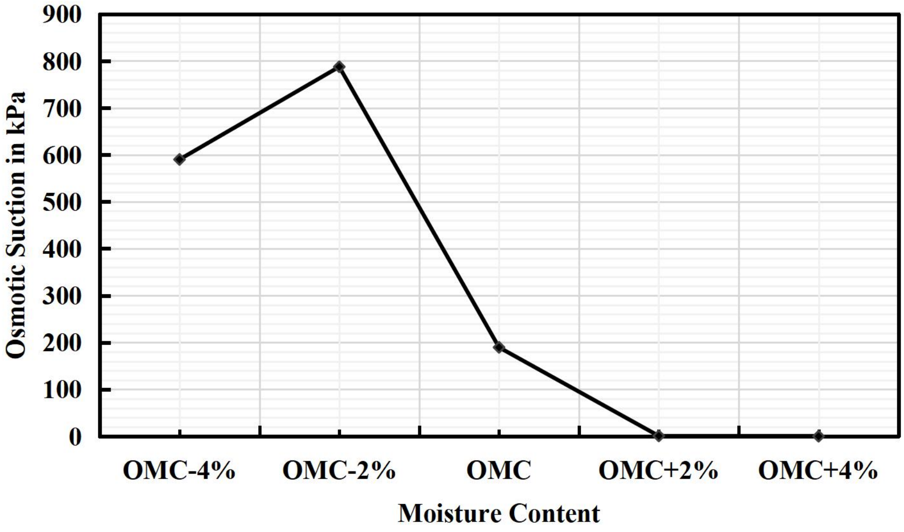

Figure 4: Osmotic suction evolution with wetting. Peak osmotic suction (787.5 kPa) occurs at OMC-2%, followed by rapid decay as pore fluid becomes diluted. Near-complete loss of osmotic potential by OMC+2% explains the vulnerability of this soil to wetting-induced collapse.

4.3 Practical Implications

For geotechnical engineers working in Rajasthan/Gujarat, these findings suggest that bearing capacity estimates based on "in-situ" suction (often measured in the dry season) are unconservative. The potential loss of ~800 kPa of osmotic suction upon wetting represents a significant loss of effective stress that is not captured by standard matric suction sensors (tensiometers). It is recommended that total suction measurements be incorporated into site investigations for collapsible soils in semi-arid regions.

5. Conclusions

This study investigated the suction characteristics of collapsible loess from Western India. Based on the experimental results, the following conclusions are drawn:

1. **Inverse Relationship:** Total suction exhibits a clear inverse relationship with moisture content, decreasing from 2,287 kPa in the dry state to 22 kPa at near-saturation.
2. **Dominance of Osmotic Suction:** In the critical transition zone (OMC-2%), osmotic suction accounts for **87%** of the total suction. This contradicts the common assumption that matric suction is the sole governing parameter in unsaturated loess.
3. **Collapse Vulnerability:** The rapid loss of matric suction at low moisture contents, followed by the loss of osmotic suction at higher moisture contents, creates a two-stage vulnerability to collapse.
4. **Design Recommendation:** Settlement predictions in semi-arid loess must account for the degradation of both capillary and chemical bonds. Tensiometers alone are insufficient for

characterizing the full stability profile of these soils; total suction measurement (via filter paper or psychrometers) is essential.

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