Effects of wetting and drying cycles on the mechanical behaviour of Lightweight Cemented Soils

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Abstract. An experimental investigation on the durability of Lightweight Cemented Soils (LWCS) after wetting and drying cycles was developed, focusing on the evolution of their mechanical response. Wetting and drying cycles were performed in climatic chamber to test their mechanical performance as function of number of cycles and the environmental conditions (50% and 90% of Relative Humidity). Unconfined compression tests and triaxial tests were performed on treated specimens after cycles in dry state. Suction of LWCS samples was measured after mechanical tests. Test results show that the wetting-drying cycles and the variations of suction are responsible for the evolution of LWCS mechanical behaviour. Moreover, strength and stiffness of the treated samples are related to the suction level induced by environmental conditions. The degradation of mechanical behaviour is linked to the number of cycles and to the amplitude of suction variation induced, being the latter responsible for mechanical cement bonding destructuration.

1 Introduction

During the construction of infrastructures, one of the main problems encountered is the allocation of excavated soil, especially if it is not suitable as construction material. The reuse of this soil by means of chemical treatments represents an important opportunity, aimed at reducing the environmental impact of the infrastructures [1]. In the field of soil improvement, a widely used solution is to add cement and foam to produce Lightweight Cemented Soils (LWCS). LWCS are prepared by mixing cement and foaming agent with clayey soils of poor mechanical properties. Thanks to their self-levelling properties and reduced unit weight by volume, LWCS are used in various geotechnical applications (i.e., embankments, backfilling of retaining structures, filling of urban cavities and excavations) [2, 3].

Studies on the effects of cement, foam and initial water content on unit weight and shear strength of LWCS have been performed, shedding light on the evolution of physical and mechanical properties as a function of treatment parameters [4, 5, 6]. Moreover, an insight into the role of foam content on chemo-physical evolution and microstructural features of the system on mechanical behaviour of LWCSs has been provided by [7], which highlighted that addition of foam does not alter chemo-physical evolution of the soil–cement–water system in terms of either cement hydration or pozzolanic reactions.

Durability of LWCS under different environmental loads has not been thoroughly investigated in the literature, even if it represents a relevant aspect for an extensive use of the improvement technique in geotechnical practice. In nature, soils are submitted to periodic wetting-drying cycles owing to the alternation of the rainy and dry seasons. Their variation produces effects on the mechanical behaviour and performance of treated soils [8-12].

Several studies have been conducted on the effects of wetting and drying cycles on the hydro-mechanical behaviour of unsaturated soils. The environmental load induces irreversible volumetric changes due to swelling and shrinkage strains [13, 14] as a consequence of changes in net stress and matric suction [15]. The evolution of mechanical behaviour of treated soil upon wetting and drying is affected by the degradation of cementation following the cyclic variation of suction induced by the environmental condition. A study on the durability of Lightweight Cellular Cemented (LCC) materials after wetting and drying cycles has been carried out by [16]. They observed a reduction of the strength due to the cement structure degradation.

An insight into the water retention properties of cement treated and lightweight cemented soil has been provided by [17], taking into account the effects of air foam content and curing time. This experimental study, aimed at determining the suction range corresponding to significant changes in water content, was preliminary to the investigations devoted to durability properties of LWCS systems exposed to wetting and drying cycles.

In the present work, wetting and drying cycles on LWCS samples have been performed in climatic chamber in order to test their mechanical performance

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as function of number of cycles and the environmental conditions (i.e. 50% and 90% of Relative Humidity). Unconfined compression tests and triaxial tests have been performed on treated samples after cycles in dry state. Suction of LWCS samples has been measured after the mechanical tests.

2 Materials and methods

2.1 Materials

Speswhite Kaolin was considered for the experimental investigation. It is an artificial clayey silt produced by *Imerys Minerals Ldt (UK)*, consisting of kaolinite clay minerals with small amount of quartz and muscovite. The liquid and plastic limits are respectively 70% and 32%. Portland limestone rapid hardening cement (CEM II/A LL 42.5R) was used as binder. The foam was produced from a commercial surfactant solution (ISOCEM/S), provided by *Isoltech s.r.l.,* with an industrial foam generator at a density equal 0.8 kN/m^3.

2.1.1 Samples preparation

Lightweight cemented (LWCS) samples were prepared in four distinct stages. In the first phase, dry kaolin was mixed with distilled water at w_{slurry}=140% (i.e. two times the liquid limit). In the second phase, cement grout was prepared by mixing anhydrous cement with water considering a water/cement ratio equal to 0.5 (w_c/c=0.5). In the third phase, the grout was added to the slurry and mixed up until a homogeneous mixture was obtained. Forty per cent of cement by dry weight of soil was selected for the treatment (c/s =40%). The fourth stage consisted of preparing the foam by blowing pressurised air at 3.2 bar into a solution of water and surfactant with concentration equal to 2.5%.

LWCS samples were prepared at foam contents of 20% and 40% by volume of the mixture (n_f = 20% and n_f = 40%).Samples were poured in PVC moulds and sealed in plastic bag in order to prevent water evaporation during cement hydration. The curing time of the specimens lasted six months. The treatment parameters are summarized in Table 1.

Table 1. LWCS: treatment parameters.

	w_{slurry} (%)	w_c/c (%)	c/s (%)	n_f (%)
SW Kaolin	140	50	40	- 20 40

In the following, samples are indicated by the acronym KC40nfX. K stands for Speswhite Kaolin, C40 is the cement content and nfX indicates the artificial porosity induced by foam in percentage. For cemented samples without foam addition the acronym is KC40. The identifications of the samples used in the following graphs are reported in Table 2.

Table 2. Identifications of the samples.

Mix	Identifications
KC40	nf0
KC40nf20	nf20
KC40nf40	nf40

On site, the mixture is prepared in a batch plant according to the mix design approach followed for samples preparation in laboratory. It is important to use a double batch that can ensure the soil slurry is prepared separately from the rest of the mixture. This avoids the breakage of bubbles during the mechanical mixing phase, which could lead to an increase in the unit weight by volume of the material due to the volume loss of foam. Normally, the mixture prepared in this way is transferred by pumping from the batch plant to the construction site, due to its significant fluidity and placed without compaction. In fact, the purpose of using this technique is to have a material with high workability in the fresh state, with self-levelling properties such that compaction is not necessary, thus considerably reducing construction time.

2.2 Experimental procedures

Wetting and drying cycles on treated samples were performed in climatic chamber considering different environmental conditions (i.e. 50% and 90% of Relative Humidity (RH)). Samples were extracted from the mould and exposed to a drying process at constant temperature of t = 20° and RH = 50%. The dry condition represents the initial reference state for all the samples. The samples were then exposed to three wetting and drying cycles, performed at constant temperature (t = 20°) and considering two different values of RH (i.e. 50% and 90%). The identifications of the environmental load conditions applied are reported in Table 3.

Table 3. Identifications of the environmental load conditions.

Environmental load conditions	Identifications
0 w-d_50% RH	A
3 w-d_50% RH	B
3 w-d_90% RH	C

The wetting phase was performed by immerging the sample in water at constant temperature of 20°C for two days. The drying phase in climatic chamber (Weiss WKL 100/+10, with a capacity of 100 litres, temperature range from +10°C to +180°C and relative humidity from 10% to 98%) lasted 5 days. A summary of wetting and drying cycles parameters is shown in Table 4.

Samples after wetting and drying cycles were submitted to suction measurements and mechanical testing (unconfined compression tests and triaxial tests). Suction measurements were performed using the WP4C Dewpoint PotentiaMeter, produced by the Meter Group. The WP4C uses the dewpoint – cooled mirror technique to measure the total suction of a sample by determining the relative humidity of the air in thermodynamic equilibrium with the soil samples contained in the thermoregulated and sealed measuring chamber of the instrument. Suction of LWCS samples was measured at the end of the wetting – drying cycles and after the mechanical tests. Unconfined compression tests were performed at constant rate of 1.05 mm/min. Triaxial tests were carried out in the controlled stress path cell, equipped with internal sensors for the measurements of local axial and radial strains. The strain rate was set at 0.1 mm/min and the tests were carried out at three different confining stress levels equal to 50, 100 and 150 kPa.

Table 4. Wetting-drying parameters.

	Temp. (°C)	**RH (%)**	**Duration (days)**	**Modality**
Wetting	20	-	2	Immersion in water
Drying		50 90	5	Climatic chamber

3 Results

Results of unconfined compression tests performed on cement treated and LWCS samples (i.e. KC40 and KC40nf20) exposed to different climatic loads (i.e. 0 w-d cycles RH=50%; 3 w-d cycles RH=50% and 3 w-d cycles RH=90%) are shown in Fig.1, a and b respectively. Compared to cemented samples, lower unconfined compressive strength (UCS) and stiffness are observed for lightweight cemented samples regardless the tested conditions. For both mixtures, at fixed RH, the number of cycles has a detrimental impact on the mechanical behaviour of the samples, leading to a reduction of UCS and stiffness. A further degradation of mechanical performance of treated samples is observed by comparing test results performed at fixed number of cycles (i.e. 3 w-d cycles) and different RH, with a reduction of UCS for samples submitted to wetting and drying cycles at RH=90%.

Suction measurements performed after unconfined compression tests and UCS results have been showed in Fig. 2. Three wetting and drying cycles performed at RH=50% on treated samples induce a significant reduction of unconfined compressive strength and a slight increase of suction values. Considering the same number of wetting and drying cycles at RH=90%, a significant decrease of suction for all the treated samples, combined with a reduction of UCS, is observed. UCS reduction is more relevant for cement treated samples compared to lightweight cemented samples (Fig. 2). Reduction of UCS is the main effect of the destructuration of cemented material due to cyclic increase and decrease of suction (respectively drying and wetting phases), whose entity depends on the suction level imposed to the samples. For the same number of wetting and drying cycles, the higher the suction level, the lower is the UCS reduction, as highlighted comparing wetting and drying cycles at RH=50% (higher suction level) and RH=90% (lower suction level).

Results of triaxial tests performed on KC40nf20 and KC40nf40 treated samples at 50% and 90% RH after three wetting and drying cycles, are shown in Fig. 3., in terms of failure envelopes in s-t plane. After the same number of wetting and drying cycles, performed at RH=50%, samples prepared with higher artificial porosity due to foam addition (i.e. KC40nf40) show lower shear strength. The effect of wetting and drying cycles at different suction levels can be observed by comparing failure envelopes of KC40nf20 samples. For higher suction levels performed during wetting and drying cycles (i.e. RH=50%), failure envelopes show the higher strength of lightweight treated samples. Suction values measured after the triaxial testing, reported in Table 5, confirm the previous interpretation, being the reduction of shear strength shown by treated samples clearly related to the reduction of suction levels.

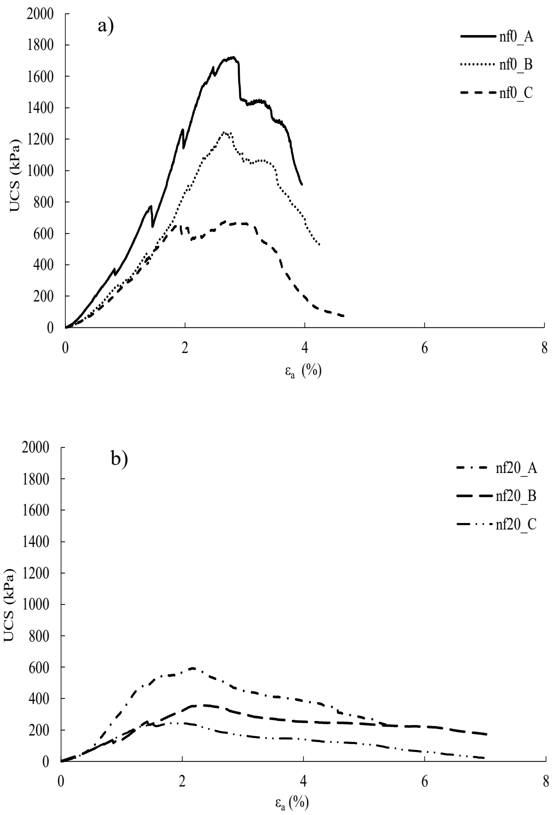

Fig. 1. Unconfined compression tests results at three different climatic loads. On the top (a), SW Kaolin c/s40%. On the bottom (b), SW Kaolin c/s40% nf20%.

For KC40nf20 treated samples, the decrease of cohesion values observed comparing samples submitted to wetting and drying cycles at RH=50% and RH=90%, without changes of friction angle, are consistent with other results reported in the literature [18, 19, 20]. The lower cohesion value pertaining to KC40nf40 sample compared to KC40nf20 after three wetting and drying cycles at RH=50% is attributed to the higher initial porosity of the sample and the subsequent lower shear strength.

The volumetric response of treated samples at 50% and 90% RH after three wetting and drying cycles, is characterized by an increase in the volumetric strains, in the passage from higher to lower suction level. This aspect is even more evident at increasing percentage of artificial porosity in the sample (i.e. from KC40nf20 to KC40nf40), due to the higher void ratio.

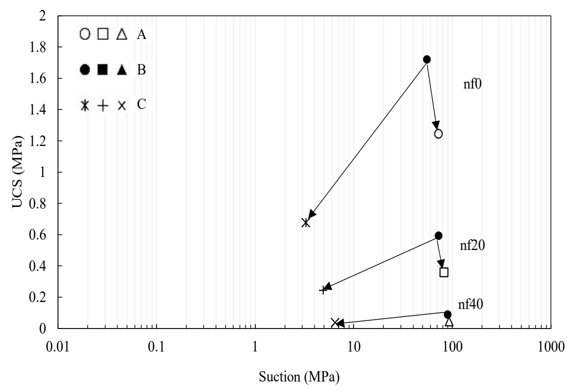

Fig. 2. Suction measurements in relation to the unconfined compressive strength values, at three different climatic loads.

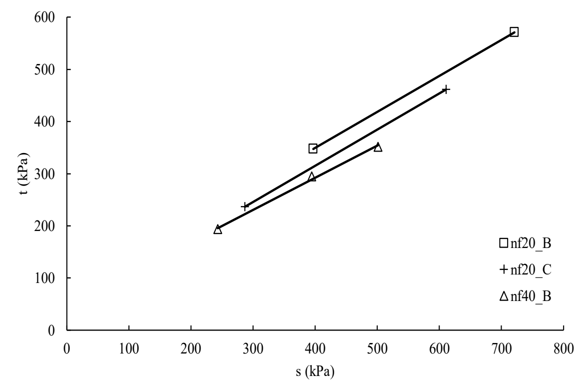

Fig. 3. Failure envelopes of KC40nf20 and KC40nf40 at 3 w-d cycles and relative humidity values of 50% and 90%.

Table 5. Suction, cohesion and friction angle values for the two different mixtures at two relative humidity values.

Mix	RH (%)	Suction (MPa)	c (kPa)	Φ (°)
KC40nf20	50	82.9	100.5	43.7
	90	4.9	53.2	43.8
KC40nf40	50	92.9	58.1	38.0

4 Conclusions

In the present work, the durability of LWCS samples has been investigated by means of mechanical testing, taking into account the effects of wetting and drying cycles. Wetting and drying cycles have been performed in climatic chamber in order to assess mechanical performance of LWCS as function of number of cycles and the environmental conditions (50% and 90% of Relative Humidity). Results of unconfined compression tests and triaxial tests showed the degradation of LWCS mechanical performance after wetting and drying cycles. The suction level induced by the imposed environmental conditions controls the amount of strength and stiffness degradation of treated samples, mainly due to cement bonding destructuration.

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